Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

1975

A decision theoretic approach to contractual maintenance

Fulgham, James Grant

University of Pittsburgh

http://hdl.handle.net/10945/20805

Downloaded from NPS Archive: Calhoun

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

A DECISION THEORETIC APPROACH TO CONTRACTUAL MAINTENANCE

James Grant Fulgham

A DECISION THEORETIC APPROACH TO CONTRACTUAL MAINTENANCE

by

James Grant Fulgham

B.S. in M.E., Mississippi State University, 1966

Submitted to the Graduate Faculties
of the Graduate School of Public and International Affairs
and
The School of Engineering
in partial fulfillment of
the requirements for the degree of
Master of Public Works
and
Master of Science
in
Civil Engineering
University of Pittsburgh
1975

Thesis
F924

Acknowledgements

The author wishes to express his gratitude to the United States Navy for sponsoring his graduate study at the University of Pittsburgh.

The author is also grateful to Dr. James P. Miller, Jr., and Professor George Tomsho for their advice and assistance throughout the author's term of graduate study.

Finally, a special note of gratitude and thanks to the author's wife, Donna, for her efficient, loyal, and tireless assistance in the typing and editing of this manuscript and to the author's sons, Brent and Brian, who endured cheerfully the many hours that the author stole from their family life.

A DECISION THEORETIC APPROACH TO CONTRACTUAL MAINTENANCE

James Grant Fulgham
University of Pittsburgh, 1975

Current trends in plant maintenance in both government and industry indicate a strong impetus toward contractual maintenance (CM). As plant processes continue to become more sophisticated and pollution control requirements add additional new processing responsibilities to the existing ones, owners are turning to CM to reduce capital expenditures, reduce operational downtime, and obtain required skills to perform specialized maintenance services. Decisions to procure complete contractual maintenance services have been deterred, however, by the inability of plant owners to develop a priori estimates of major maintenance requirements for the contract period and to describe the re-

quirements in a complete set of plans and specifications. Accordingly, in order to maintain control over the contract forces and ensure that plant maintenance policies are carried out, most plant owners procure CM through labor brokerage contracts, on a unit cost basis, or enter into cost-plus arrangements that allow limited supervision of CM forces by the owner.

Plant owners are now faced with the dilemma of requiring complete CM services from outside sources on the one hand, and ensuring that plant maintenance policies are fulfilled without an a priori description of each potential maintenance act to be performed on the other hand. In order to solve the dilemma, since there can be no a priori assessment of the ultimate scope of work that may be needed during the contract period, a contract basis is required that exerts a legally enforceable obligation on the contractor to generate the plant maintenance requirements through continuous inspections during the contract period, to plan and estimate the resources required to fulfill each requirement as it arises, and to subsequently schedule the performance of the work in accordance with priorities established by plant maintenance policy. Since the contract bids or proposals will tend to be in proportion to the subjectively assessed risk involved, the contract should be low risk but at the same time it should provide incentive to maintain the plant

in accordance with plant maintenance policy.

An existing maintenance contract that approaches the proposed format is analyzed as it applies to generation of work, planning, and scheduling. The key feature missing from the contract analyzed is the decision model required to control job priority and scheduling decisions and ensure compliance with plant maintenance policy.

A decision model is developed for the contract being analyzed and implementation of the revised contract is discussed.

DESCRIPTORS

Assessor
Bid items
Contractual maintenance
Decision theory
Efficiency
Incentive
Level of maintenance
Maintenance management
Plant
Priority
Production
Quality control
Reliability
Reward structure
Scheduling
Subjective probability
Threshold evaluation
Utility

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ii

ABSTRACT iii

LIST OF FIGURES. viii

1.0 INTRODUCTION. 1

- 1.1 General. 1
- 1.2 Objective. 7
- 1.3 Significance 8
- 1.4 Methodology. 11
- 1.5 Limitations to the Methodology 14

2.0 WHAT'S HAPPENING IN THE CONTRACT MAINTENANCE MARKETPLACE 16

- 2.1 The Contract Maintenance Consumer Preference 16
- 2.2 Existing Practices and Attitudes 18
- 2.3 The Guantanamo Contract Experience 23
- 2.4 Complete Contract Maintenance: A Definition 27
- 2.5 The Current Dilemma. 28

3.0 PROGRAMMING DECISIONS: A ROLE FOR MAINTENANCE MANAGEMENT. 30

- 3.1 General. 30
- 3.2 The Plant Manual 33
- 3.3 The Preventive Maintenance Inspection System. 39
- 3.4 Planning 45

3.5 Resource Constraints: Establishing the Decision Boundaries 48

4.0 WORK INPUT CONTROL: CONTRACTOR DECISIONS VERSUS OWNER INTERESTS 54

4.1 A Choice Among Alternatives 54

4.2 A Decision Theoretic Approach 55

4.3 A Multi-Attribute Utility Model 71

4.4 Scheduling. 81

5.0 A NATURAL IMPUTED REWARD STRUCTURE 86

5.1 General 86

5.2 The Profit Incentive. 87

5.3 A Measure of Effectiveness. 91

5.4 A Reward to Engender Honesty. 94

6.0 CONCLUSION 100

6.1 Summary 100

6.2 Implementation. 115

APPENDIX A. 129

APPENDIX B. 161

BIBLIOGRAPHY. 171

REFERENCES NOT CITED. 178

LIST OF FIGURES

Figure No. Page

1 Maintenance Management System. 32

2 Elements of the CQC System 42

3 Detailed Maintenance Job Planning Chart. 47

4 Guantanamo Evaporator MAU Structure. 78

5 Guantanamo Evaporator Work Input Control Model. 80

6 The Proposed Complete CM Contract System. 109

1.0 INTRODUCTION

1.1 General

Each year as pollution control statutes become increasingly more stringent in the application of effluent standards, government and industry find it necessary to build new sophisticated treatment plants or to add additional new equipment to existing treatment plants to process their refuse and waste effluent. This marked increase in process requirements has come at a time when the nation is in a continuing period of rapid technological change. In many cases, the agencies or industries involved have been unable to obtain "in-house" the quantity and quality of manpower and equipment needed to facilitate the technological changes or meet the new processing requirements. Accordingly, one solution to this problem has been to procure the needed services from contract sources. A major service area that has achieved a great increase in contract procurement has been plant maintenance.(1)*

Although contractual maintenance (CM) is widespread, this area of contracting is the subject of great controversy. In order for contractual maintenance to be a viable

---

*Parenthetical references placed superior to the line of text refer to the bibliography.

alternative to force account* maintenance its implementation should cost no more than the initial manpower and capital equipment acquisitions, manpower development, and subsequent operational expenditures necessary to perform the service by force account. Moreover, the owner's interests should be protected at least as well as they are perceived to be protected through force account maintenance. However, there is evidence that many plant owners do not believe that CM will cost less and protect their interests as well as force account maintenance and there is, therefore, a great deal of resistance to complete CM by those owners.

A clearer view of the CM controversy can be gained when one analyzes the nature of plant maintenance and the existing contract arrangements commonly used to fulfill the plant maintenance requirements.

By nature, plant maintenance covers two areas of maintenance action commonly called preventive maintenance (PM) and corrective maintenance. PM requirements can be anticipated a priori** and corrective maintenance requirements cannot. In this regard, since corrective maintenance requirements cannot be anticipated a priori with certainty, the maintenance decision maker is faced with uncertainty

---

*Maintenance carried out by plant owner employees and equipment.

**Before the fact.

when estimating the expected cost of maintaining the plant for the next maintenance period. Accordingly, contractors preparing a proposal for a CM service must perceive this uncertainty as a "risk" and when faced with a contractual pricing arrangement that places the plant maintenance risk on them, the contractors must assign an expected value to that risk and include it in their proposal. Depending on the degree of risk assigned to the contractor, then, the owner will pay an immediate premium for the contractor's risk that would not necessarily arise as an explicit immediate cost in force account maintenance.

Because of the risk premium implied in any "fixed-price" contract many owners who desire CM services have procured these services through "cost-plus" agreements whereby the owner pays the contractor all of his costs plus some agreed upon profit. Obviously, this type of pricing arrangement provides little incentive for the contractor to reduce costs or protect the owner's interests since his profit is, in most cases, not affected by those factors.

In order for complete CM to be a viable alternative to force account maintenance, a contract framework with a low-cost pricing arrangement (relative to the force account alternative) and controls that protect the owner's interests must be provided. Since the contract cost will be in direct proportion to the contract risk assessed by the contractor,

a more descriptive statement of the contract framework requirements would be (a) low contractor risk and (b) protection of owner interests.

Considering the low contractor risk requirement on the contract framework and the uncertainties inherent in plant maintenance, it is apparent that the fixed-price pricing arrangement would not meet the low risk test. Similarly, the need to control costs and protect the owner's interests obviates the cost-plus pricing arrangement. Obviously, then, since these two pricing arrangements comprise the opposite poles of pricing arrangements, a contractual framework must be developed that includes a pricing arrangement that falls optimally between these two poles. In this regard, a framework is implied that should tend to minimize contractor risk and maximize protection of owner interests.

Since the contract framework proposed to be developed must be low cost and protect the owner's interests relative to any alternative force account framework, it is logical to assume that the contract framework might be constructed similar to a successful force account framework for plant maintenance. A contract is nothing more than an agreement (oral or in writing) between two parties wherein one party agrees to provide goods or services to another party in return for other consideration. Allegorically, a contract between a plant owner and a contractor is similar to an employment

agreement between an employer and an employee. In the context of plant maintenance, the owner's employees have agreed to provide the services needed in return for their pay. It is axiomatic in force account plant maintenance that the quasi-systems analysis approach to maintenance, termed "maintenance management," is used to protect the owner's interests.

Within the maintenance management system, the decisions to be made under uncertainty in regard to corrective maintenance are controlled by owner guidelines and informal decision models expressed as plant maintenance policy. The employees have incentive to make decisions that are in the owner's interests because wrong decisions could result in dismissal and right decisions could result in promotion. In the force account framework, costs are relatively low since the owner pays no immediate risk premium and the owner perceives that his interests are protected to the extent that his employees are motivated by the explicit or implicit incentives that he provides them.

It would appear, then, that a complete CM framework could be developed that would merge the systems analysis concept of maintenance management, an owner decision model to control decisions made under uncertainty, and a contractor incentive feature. Both maintenance management and contractor incentive concepts have been and are being

applied to CM. The use of owner-derived decision models has had successful application in industrial production scheduling and other areas similar to maintenance decision making.

Because of the risk premium involved in fixed-price contracts most CM clients procure CM through cost-plus agreements and protect their interests by maintaining direct control over work scheduling or providing direct supervision of contractor forces. Even with CM agreements that include the features of maintenance management and contractor incentive, the owners feel that they must maintain control over work priority assignment in order to protect their interests. Indeed, most of the criticism of the complete contractual maintenance concept centers around one issue: How to resolve autonomous contractor decisions with owner interests.(2)

It is reasonable to assert that the merging of the concepts of maintenance management, owner-derived decision model, and contractor incentive into a single contract framework will provide a framework superior to the existing cost-plus framework for the following reasons:

(a) most existing frameworks provide no ceiling on costs, proposed framework will;

(b) existing frameworks require active owner supervision of contractor forces to protect his interests, pro-

posed framework would disengage owner from contractor; and

(c) most existing frameworks provide little incentive for contractor to improve plant performance, proposed framework will.

The literature contains much information on the theory of maintenance management and incentive contracts. Since these subjects are adequately covered elsewhere, it is the purpose of this thesis to develop a CM work priority assessment and scheduling model that will approach a resolution of the contractor decision versus owner interests dilemma. Additionally, the rationale for merging the concepts of maintenance management, decision model, and contractor incentive into a comprehensive improved CM framework will be developed and recommendations made for implementation.

1.2 Objective

The objective of this thesis is to develop a work priority assessment model for a complete contractual maintenance agreement for the maintenance of a 750,000 gallon-per-day multistage flash evaporator. The role of the model in melding the systems analysis concepts of maintenance management and the motivational concepts of contractor incentive into a comprehensive contractual framework shall be discussed.

1.3 Significance

The contractual maintenance dilemma as perceived by a client was best expressed by Mr. Donald Wanner, Chief Engineer, Columbia Nitrogen Corp., during a round table discussion of the pros and cons of CM in which he said:(3)

> "The discussion here stresses the fact that the owner must maintain some continuity for control purposes in the maintenance operation. This almost demands that we go the route of something less than total CM. Only in this way can you have the necessary interface between the contractor and the owner to the extent that the owner can maintain the direction and control of the overall maintenance function and the contractor can handle the day-to-day situations."

Although there is a propensity on the part of many plant owners to procure complete CM services, they often fall short of their desires because of issues similar to the ones raised by Mr. Wanner. In general, plant owners are advised to enter CM agreements only if the maintenance work being considered meets the following conditions:(4)

(a) work under consideration can be identified by some measurable unit (cubic yard, etc.) to enable a contractor to formulate a bid;

(b) the work can be estimated in advance to insure that bids received are reasonable;

(c) the work can be described adequately by a set of plans and specifications;

(d) the work can be scheduled, and contract time calculated;

(e) technical expertise is available among possible successful bidders;

(f) a demand exists for the contractor industry to enter into maintenance contracts.

The usual result has been that plant owners are unable to fulfill one or more of the conditions and they resort to something less than complete CM as supported by Mr. Wanner's statement.

The most common CM framework used is the maintenance management approach with owner control of work priorities and a cost-plus pricing arrangement. This approach provides little incentive for cost reduction, efficiency, or performance improvements, and requires the owner's direct participation in the day to day maintenance activity of the contractor.

The significance of this study is that it proposes a way to extract the owner from involvement in the day to day plant maintenance activity and to provide motivation for the contractor to reduce costs and improve efficiency and plant performance. The system proposed in this study offers a viable alternative to the labor brokerage or owner supervision agreements usually entered when a firm performance specification for CM cannot be produced. The most

significant feature of the model developed in this work is that when considered in the context of complete CM it approaches a resolution of the autonomous contractor decisions versus owner interests dilemma.

In developing the model and framework for complete CM, the three basic components proposed for complete CM, i.e., maintenance management, decision model, and contractor incentive have each been used in situations applicable to plant maintenance. Although maintenance management and contractor incentives have been used directly in maintenance contracts, there is no evidence that an owner-derived decision model has been used in CM. However, owner-derived decision models have been successfully used in industrial production scheduling and it is therefore reasonable to assert that similar models can be applicable to maintenance scheduling. Since there is no evidence that a practical application of the owner-derived decision model concept has been made in CM no direct data can be provided to support the contention that such a model can protect the owner's interests.

Without prima facie evidence, however, a strong case can still be made in support of the owner-derived model concept in CM based on successful applications of such models in other areas. It shall be asserted in this thesis that maintenance decision making is not unlike any

other type of decision making. The decision maker first searches the environment for alternative situations calling for decisions, he plans for the acquisition of resources necessary to satisfy each alternative, then he selects an optimal act from the set of alternatives for accomplishment. Managers follow this procedure in maintenance management, production control, and any other scheduling process. It seems logical to assert, then, that if a particular decision making concept has proven useful in one scheduling process, then, it should tend to be equally useful in a similar process.

Based on the rationale presented above, the owner-derived decision model is considered a viable concept for CM insofar as it has been used successfully in industrial production scheduling. An in-depth analysis of the owner-derived model and the viability of such models is presented in Chapters 4 and 5.

1.4 Methodology

A firsthand knowledge of the administrative problems and deficiencies encountered with maintenance contracts was obtained during an assignment involving the administration of the operation and maintenance contract for the Combined Seawater Conversion and Power Plant, Guantanamo Bay, Cuba, from 1971 to 1973. This experience indicated that

the contract client (the U.S. Navy) desired a complete contractual maintenance service, but fell short of this goal due to the administrative difficulties that arose from the ambiguity inherent in allowing autonomous contractor scheduling decisions and at the same time attempting to ensure that plant maintenance policy was fulfilled. Subsequent research has determined that the desire for complete CM services is widespread but that the procurement of these services is impeded by the same dilemma that faced the Navy at the Guantanamo plant.

This work proposes a possible way to resolve the dilemma faced by CM clients. Based on the experience with the Guantanamo contract, research was conducted into the overall magnitude of the problem as follows:

(a) current literature including trade journals, publications of professional societies, periodicals, and textbooks was reviewed;

(b)interviews with engineers and managers at the federal and local levels and with industry were conducted;

(c) a review was made of the lessons learned from the Guantanamo contract.

The system for a resolution of the CM problem is developed using proven maintenance management, decision theory, and contractual incentive principles derived from research in the publications of professional societies, periodicals,

and textbooks.

Chapter 2 provides the background for the thesis and qualitatively defines the current contract maintenance dilemma. Chapter 3 provides the reader with an introduction to maintenance management and describes a proposed CM framework using maintenance management principles. Chapter 4 provides the essence of the thesis. In this chapter, a decision matrix, multi-attribute utility model is developed for making job priority decisions in the maintenance of an existing 750,000 GPD evaporator. This particular plant is chosen because of first hand knowledge and the fact that a practical illustration of the decision theoretic principles can best be made using an existing plant. It will be shown in Chapter 4 that the assessment of subjective probabilities by the contractor plays a major role in the successful maintenance of the plant. Therefore, Chapter 5 defines a system of bonuses and penalties that gives the contractor incentives to be honest in his assessment of the subjective probabilities. Finally, Chapter 6 concludes with a summary of the factors discussed in the thesis and provides a recommended method of implementation of the system in a contract.

1.5 Limitations to the Methodology

The contract maintenance controversy centers around the issue of how to resolve autonomous contractor decisions and owner interests. In order to minimize the magnitude of this dilemma, the first step toward solving it should be to minimize the opportunities that a CM contractor would have to make decisions that might conflict with the owner's interests. One way to minimize the contractor's opportunities in this area is to develop a maintenance system that incorporates programmed decisions vice unprogrammed decisions. For example, if the owner has a preventive maintenance system operational in his plant, the PM procedures and maintenance decisions involved in PM are programmed within the PM system. Each step is clearly written down.

The adaptation of this decision opportunity minimization principle in this thesis places certain limitations on the applicability of the model to CM contracts in general. The following conditions should be met before consideration is given to adopting the model developed in this thesis:

(a) the "plant" to be maintained is of adequate size and sophistication to warrant the development of a formal maintenance management program for its maintenance;

(b) the owner of the plant has a comprehensive maintenance management system for the plant contained in a plant manual;

(c) manufacturers literature exists on all major plant components;

(d) a complete set of as-built plans and specifications exists on all major plant components;

(e) the plant is initially in good condition so that potential maintenance contractors would not anticipate undue maintenance risks in the preparation of bids;

(f) either the contract is written for complete maintenance and operation of the plant, or maintenance and operations are clearly separated in the contract specifications so that there is no overlap or possibility of interference between the operating forces and maintenance forces;

(g) contracting out of the complete maintenance service is not in violation of any existing fair labor laws, practices, or agreements with labor unions;

(h) all maintenance contractors are rational;

(i) all maintenance contractors prefer more profit to constant or less profit.

2.0 WHAT'S HAPPENING IN THE CONTRACT MAINTENANCE MARKETPLACE

2.1 The Contract Maintenance Consumer Preference

According to Oliverson,(5) "There is a general feeling that the next decade will see a steady growth in the use of contract maintenance to help maintain equipment that is continually becoming more sophisticated." Statistical evidence of the extent to which contractual maintenance is being used in industry is provided in the results of a survey of 100 chemical process plants conducted by Mr. J.W. Sarappo(6) in 1969. It was determined that 90% of the plants had at one time used contract maintenance and 74% used contract maintenance to supplement plant forces at the time of the survey. In the plants using contract maintenance at the time of the survey, 20 to 30% of the plants' total employment constituted contract maintenance workers.

The importance of contract maintenance (CM) in process plants is apparently well established. Some important questions are: What kind of maintenance service do the clients of CM prefer? If CM clients were free to choose, would they opt for labor brokerage contracts or for complete contract maintenance?

In order to obtain meaningful answers to these questions, PLANT ENGINEERING conducted a contract maintenance

roundtable in June, 1972, with a representative panel composed of contract maintenance suppliers, contract maintenance users, an inplant maintenance advocate, and consultants. A representative opinion of a contract maintenance user is expressed by Mr. Truett Newbrough, President, Albert Ramond and Associates, who states:(2)

> "This is really the first time I've had a chance to hear contractors express themselves and it's very enlightening. I can't help but feel that the desirable thing would be for the contractor to take over the whole maintenance function and yet I think, from the practical standpoint of the user, this poses some serious questions. He likes to keep that control, including scheduling and some kind of control over stores, and so on."

Additional support for the view that the contractor should take over the whole maintenance function is provided by Rohrmann:(7)

> "At Getty Oil's Delaware City Refinery, contract maintenance is considered a professional service that supplies an adequately skilled labor pool, experienced engineering facilities and many other types of necessary, allied services. This definition is given to eliminate any confusion with the 'labor broker' who merely supplies manpower for disposition by the client's supervisory force supplementing the existing maintenance force for intermittent periods."

Existing maintenance contracts are lauded for the degree to which they approach complete CM by Grey,(8) Oliverson,(9) and Flesca.(10) Most significantly, RCA's services division anticipates a broad market for a complete CM service and has coined a new term for complete CM -- "terotechnology".(11)

There appears to be a strong preference for complete CM services by many users. Although many owners are deterred from procuring complete CM because of the contractor scheduling decision dilemma, there is evidence that existing practices and attitudes are changing and the trend is toward complete CM.

2.2 Existing Practices and Attitudes

Much of the literature on contractual maintenance is devoted to establishing necessary conditions and restrictions that must be met before a plant owner should make a contracting-out decision. Price(4) and Corsano(12) recommend the following:

> "(a) work under consideration needs to be identified by some measurable unit (cubic yard, etc.) to enable a contractor to formulate a bid;
> (b) the work must be capable of being estimated in advance to insure that bids received are reasonable;
> (c) the work must be capable of being described adequately by a set of plans and specifications;
> (d) the work must be capable of being scheduled, and the contract time must be calculated;
> (e) technical expertise must be available among possible successful bidders;
> (f) a demand must exist for the contractor industry to enter into maintenance contracts."

Martin(13) analyzes present contracting practices for the Department of Public Works, City of Fresno, California, and cites specific examples that show that the city

of Fresno considers the six principles listed in making contracting-out decisions. Previous bad experience in dealing with the contractor decisions versus owner interests dilemma is evident in the following statement by Mr. Martin:

> "...How does the maintenance manager know whether a specialty contractor (elevators or air conditioning, for example) is simply replacing parts, rather than really diagnosing trouble, whether he is doing the preventative maintenance necessary to obtaining maximum equipment life, and whether he has really tuned the equipment for optimum input-output ratios? We have had some bad experience with outside maintenance contracts on vehicles in which the contractor was making decisions based too much on what was needed to get him through the period of the contract...Can we permit a contractor to make economic decisions for us regarding parts and schedules, and can we retain maintenance management personnel sufficiently knowledgeable on all technical details of a contract operation to protect the agency's interests? The career service public employee must live with and be responsible for the results of his decisions, but most contracts are for fairly short periods."

Most plant owners share Mr. Martin's concern over the contractor scheduling dilemma. However, the expected advantages of complete CM services to plant owners has provided impetus to a movement to circumvent the contractor scheduling dilemma. The literature contains evidence that many plant owners are finding it advantageous to innovate new contracting approaches in order to procure complete CM services when one or more of the stated conditions for contracting-out cannot be met. A review of journal publica-

tions on several innovative contracts was conducted to determine if any innovative features were in common among the contracts or if each plant owner had developed a technique that was suitable to fulfill only his specific needs. It was found that all of the surveyed successful complete CM contracts have one thing in common: The specification of the principles of maintenance management as part of the contract.

Oliverson(14) cites NASA's CM contract with Mason-Rust at the Michoud base in New Orleans. Mason-Rust performs the following services at the base: maintenance, engineering, utilities, transportation, port operations, safety and security, photography, reproduction, communications, medical, food and custodial service, supply, procurement, property records, and waste disposal.

The contract includes the following specific maintenance management features: preventive maintenance program, planning and scheduling of work, technical field assistance, and cost control. On general repair work, no work request form is required -- Mason-Rust automatically moves in and does the job. When modifications are desired to improve tenant capabilities, a standard work order form is sent to the Mason-Rust Division Manager's office where it is evaluated for justification. If it is determined that the work is justified it is planned and estimated and sent to NASA's

facilities office for final approval. The division manager, Mr. H.C. Bradford, states:(15)

> "The most important reason for the success of our operation is people. Get them enthusiastic, get them involved, and no job is too big. Remember, no person is completely self-sufficient...We have to have the help of others to do our job well. This goes up the line right to our general manager."

Although the contract is apparently cost-plus the above statement would indicate that NASA's interests are protected to the extent that Mason-Rust needs to maintain good will. The incentive to do a good job for NASA is basically due to the need of the Mason-Rust personnel to be important to the functions supported.

Rohrmann(16) cites the CM contract at Getty Oil's Delaware City Refinery. Specific maintenance management principles included in the contract are: a formal work order system which requires a Getty supervisor's approval before any work can proceed by the contractor; a planning and scheduling system, operated jointly, that insures efficient and economical usage of men, equipment, and material; a daily labor cost report that permits a comparison of actual performance against estimates; work sampling taken on a random basis jointly by Getty Oil and the contractor to check productivity; random checking of schedules to prove their effectiveness. Although the Getty Oil contract is cost-plus a percentage fee, Mr. Rohrmann suggests that the con-

tractor has the incentive to do a good job through the possibility of losing the contract if he does not.

Grey(17) provides suggestions on developing a maintenance management contract based on his experience with Oxochem Enterprise, Ponce, Puerto Rico. A key suggestion by Mr. Grey is that a performance award feature be included in the contract. He says:

> "Develop a list of performance elements that you, your staff and your contractor consider to be important as indicators of good maintenance. Three or four basic divisions such as Planning, Management, Craft Skills, and Turnaround Execution can be broken down into subelements. Assign weights to each element, with a total of 100. The final cumulative score will be something below 100 percent and can be used as a basis for an additional performance bonus."

Mr. Grey has found CM rewarding. He feels that the more responsibility you assign your contractor with proper rewards for performance, the more efficiently he will perform.

Flesca(18, 19) cites maintenance management principles as features of an effective CM contract based on his experience as manager of contract maintenance for Catalytic, Inc., Philadelphia, Pa. He states:

> "In the final analysis, the short and long term success of a maintenance program will depend on how well the fundamentals of good maintenance practice are applied. Invariably, excessive maintenance costs are directly related to the abuse of basic elements of good practices, such as:
>
> 1. A work request system for job delineation and authorization.
> 2. A work planning function to chart the

> course for maintenance activities.
> 3. A priority system to control work sequence.
> 4. A maintenance department budget.
> 5. A schedule to relate total authorized tasks to priorities, time, equipment outage, and available manpower, and to establish a logical flow of work."

In order to provide incentive for the contractor to perform in the owner's best interests, Mr. Flesca suggests that the contract should permit cancellation of services without obligation on the customer's part.

The contract techniques cited all contained a specification of preventive maintenance, planning and estimating, scheduling, and a consideration of contractor incentive. It is reasonable to state, then, that for those plant owners desiring complete CM services there is a trend toward the inclusion of these maintenance management specifications in the contract.

To gain a clear view of the importance of the inclusion of maintenance management principles in a complete CM contract, a particular example of a contract that experienced an evolution from the classical labor brokerage format to a complete CM format is analyzed below.

2.3 The Guantanamo Contract Experience

The U.S. Naval Base, Guantanamo Bay, Cuba, is located on the southern tip of Cuba about 900 miles south of

Miami, Florida, in the Caribbean Sea. Until 1964, the Naval Base had received its water supply from a private Cuban contractor who pumped the water from the Yateras River near the base. In 1964, after a prolonged political confrontation between the U.S. and Cuba, the Cuban Prime Minister, Fidel Castro, terminated the water supply to the base. President Lyndon Johnson then ordered that the base be made self-sufficient for water and work began immediately to build a combined seawater conversion and power plant.

In 1965, when the plant was completed, the Navy determined that because there was inadequate manpower with the necessary equipment and skills locally available to operate and maintain the plant, these functions could best be performed by contract.

The original contract was essentially a labor brokerage contract whereby the contractor provided the number of personnel and skills negotiated for and the owner provided informal direction. In this type of contract, the Navy was able to maintain direct control over plant maintenance policy and provide limited supervision over the contractor maintenance forces. In this regard, the Commanding Officer was assured that his best interests were always being served in the area of plant maintenance.

It was subsequently determined, however, that a contract of this type was a personal services contract and

might have been in violation of Navy regulations against such contracts. Therefore, the Commanding Officer was obliged to revise the contract procedures and relinquish plant maintenance control and work force supervision to contractor management.

Since the contractor was thereby controlling plant maintenance with no guidelines to protect the Navy's interests in the plant, it was recognized that a plant manual was required to outline specific maintenance procedures to be followed by the contractor. In 1968, a 5-volume plant manual was written, under separate contract, and when completed it contained all operation and maintenance procedures to be performed by the contractor. The plant manual was made a part of the contract.

The contract had then evolved from the labor brokerage format through a stage in which the contractor controlled maintenance with minimum formal contractual guidelines to a stage in which the contractor controlled maintenance but in accordance with formal procedural guidelines. A key element was still missing: There was no formal maintenance management program specified in the plant manual.

By 1971, an extensive backlog of maintenance and repair work had developed in the plant. However, the contractor was not formally planning and scheduling work and there was no explicit quantitative indication of the extent

of the backlog. The plant owner had received no management reports clearly indicating the amount of resources that should be allocated to plant maintenance.

Operational difficulties directly related to plant maintenance deficiencies were experienced in 1972 and a study team was dispatched by the plant owner to determine the causes of the problem and make recommendations for the correction of deficiencies. A major recommendation from the final report of the team was the following:(20)

> "1. Rewrite Section II of the Desal Plant Contract to require the contractor to organize to fulfill the following maintenance management functions:
>
> (a) continuous inspection;
> (b) planning and estimating;
> (c) work input control;
> (d) material coordination;
> (e) job scheduling;
> (f) management reports."

This recommendation stemmed from the finding of the study team that the contractor was not performing maintenance management and that maintenance deficiencies were a direct result of that fact.

The fiscal year 74 contract was written to include the six features recommended and action was immediately taken to update the plant manual to include a preventive maintenance inspection system and a formal maintenance management program. Current indications are that due to the implementation of formal maintenance management procedures

in the contract and the fact that the contractor is obliged to follow those procedures, the plant is now being maintained at a satisfactory level of maintenance.(21)

The Guantanamo contract experience provides testimony to the fact that when complete CM is desired by the owner of a plant, the basic principles of maintenance management must be made a part of the contract specification. This statement is further supported by the successful complete CM practices of NASA, Getty Oil, Oxochem, and Catalytic, Inc., cited in Section 2.2. In this regard, it seems appropriate to develop a comprehensive definition of complete contractual maintenance in order to crystallize the facts determined thus far and establish a unified basis for understanding throughout the remainder of this thesis.

2.4 Complete Contract Maintenance: A Definition

As supported by the facts stated above, the principles of maintenance management are so basic to the successful long-run maintenance of a facility that it is logical to define complete contract maintenance to include these principles. Therefore, complete contract maintenance is defined as the procurement by contractual agreement of the following services:

(a) the continuous preventive maintenance inspection of all plant facilities and generation of inspection reports

on all major defects;

(b) the planning and estimating of the correction of all reported defects;

(c) the formal scheduling of the correction of defects in accordance with owner policy and within resource constraints;

(d) the coordination and management of material procurement, expediting, storage, and security;

(e) the performance of all work scheduled;

(f) the administration of comprehensive management reports and follow-up.

Each of these factors will be treated in more detail in Chapter 3 with emphasis on the first three factors. It should be noted here that the six maintenance management principles included in the complete CM definition are in agreement with the common elements of maintenance management systems recommended by Rohrmann,(7) Grey,(8) Flesca,(19) the U.S. Navy,(22) and those systems researched by Corsano.(23)

2.5 The Current Dilemma

In order to establish a sound basis from which to develop the remainder of this thesis, it is important to review the points previously covered and project the logical implications of those points. First, it has been shown that the demand for contract maintenance is significant, particu-

larly in the private sector, and many plant owners prefer to have a contractor take the responsibility for the entire maintenance operation of their plant(s) rather than act as a labor broker. Second, it was shown that a number of plant owners, including both public and private agencies, have developed contracts that include the maintenance management fundamentals as performance specifications in order to assure a complete maintenance service and protect the owner's interests. Third, it was shown that most plant owners considering the procurement of a complete maintenance service oppose relinquishing scheduling authority to the contractor. Fourth, complete contractual maintenance was defined as the procurement by contract of the following six services: inspection, planning, scheduling, material coordination, work performance, and management reporting.

The key implication of these points is that plant owners who desire a complete CM service want to have a total service, including scheduling; the owners, however, see a risk in agreeing to contractor autonomy in the work scheduling area. The current attitude of owners is that to grant contractor autonomy in schedule decision making automatically implies a loss of owner control over plant maintenance policy. Plant owners, therefore, face the dilemma of how to resolve contractor autonomy and owner interests. This is the essence of the contract maintenance controversy.

3.0 PROGRAMMING DECISIONS: A ROLE FOR MAINTENANCE MANAGEMENT

3.1 General

Given the definition of complete CM developed in Chapter 2, it is axiomatic that a complete CM contract will include the six fundamental principles of maintenance management as performance specifications. It is not the goal of this chapter to justify the role of maintenance management in the protection of the owner's capital investment, since this subject is adequately covered by Corsano,(24) Hall,(25) McGuire,(26) Sargent,(27) the U.S. Navy,(28) and many others. This chapter will analyze maintenance management as a decision making system and discuss the utilization of this system in complete CM.

It is a simple matter to state that a complete CM contract should include the specification of continuous inspections, planning, scheduling, material coordination, work performance, and management reports, but when one analyzes the implications of this statement several questions arise: inspect what and how often, schedule what work and how much, order what kind of materials, and so on. In order to minimize these uncertainties on the part of the contractor the performance specifications in the complete CM contract must include built-in controls that provide answers to these

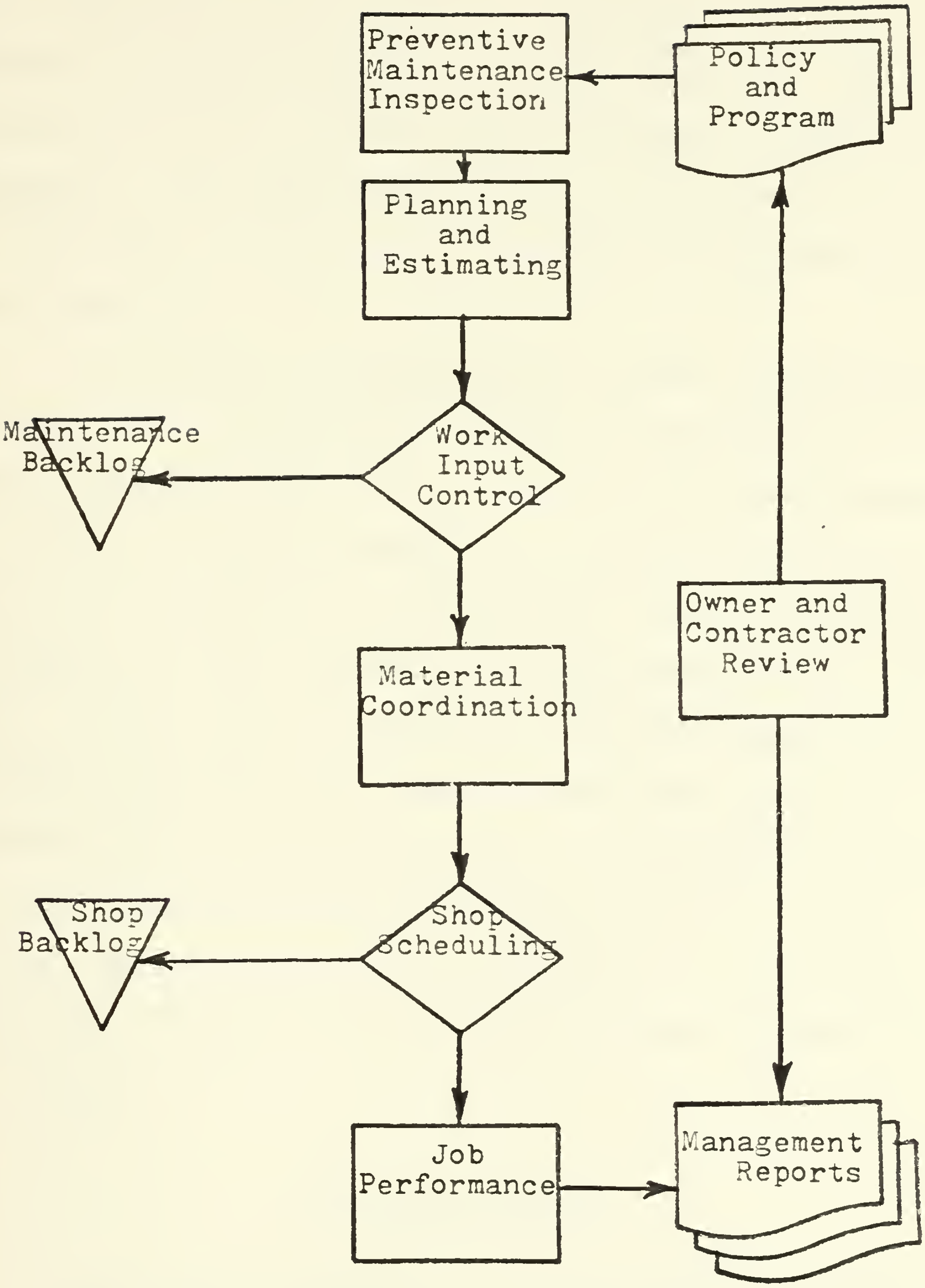
questions as they arise.

The owner must provide a precise description of the maintenance management program that the contractor is to carry out in a source reference easily accessible by any interested party. Prior to the preparation of a competitive bid or proposal the contractor must be certain of what he will be obligated to do should he be the successful bidder.

Insight into the logical structure of the maintenance management program and, accordingly, the structure of the reference document describing the program, can be gained by flowcharting the sequential elements required in maintenance management. Figure 1 provides an illustrated view of the basic elements of a maintenance management system. A review of the sequential work flow in Figure 1 shows that it follows the same procedural structure as information flow in any management decision process.(29, 30) According to Simon, managers approach decision making in three steps or activities:(31)

(A) The intelligence activity - the manager searches the environment for conditions calling for a decision. This is analogous to the preventive maintenance inspection element in maintenance management.

(B) The design activity - the manager plans for the acquisition of resources necessary to take possible courses of action. This is analogous to the planning and estimating function in maintenance management.



Maintenance Management System

Figure 1(29, 30)

(C) The choice activity - the manager selects a particular course of action from those available. This is analogous to the work input control function in maintenance management. The remaining functions of maintenance management are merely actions and follow-up resulting from the choice activity.

Maintenance management has no unique characteristic that separates it from any other type of management decision making. Therefore, the plant owner can frame the description of his maintenance management program so that the contractor initiated work flow will follow the same logical steps that the owner would use in making maintenance decisions. In most cases, maintenance management programs for new plants are developed during or soon after plant construction and are incorporated into a comprehensive operation and maintenance manual for the plant.(32) It is a simple matter to revise the plant manual for contractual purposes and reference it in the detail specifications of the contract.

3.2 Plant Manual

Maintenance management is essentially a management decision making process. To protect the owner's interests, it is important that as many maintenance management decisions as practical be programmed within the contract speci-

fications. It is asserted that the reduction of the opportunity for the contractor to make autonomous maintenance decisions contributes to the goal of protecting the owners' interests. Owner guidelines should be available to tell the contractor where, when, how, and under what conditions to make maintenance decisions. To answer these basic questions, a unified source document containing the plant inventory and the maintenance management program is necessary. Most plants, whether maintained by contract or force account, will have this information contained in a plant manual.

For an illustration of some of the information that should be included in a plant manual, Appendix A provides a detailed description of the planned maintenance management system for the 18-mgd Lower Potomac Wastewater Treatment Plant of Fairfax County, Virginia. Since the U.S. Environmental Protection Agency proposes this system as a "model maintenance management program for wastewater treatment plants throughout the United States,"(33) it is reasonable to adopt the framework of this system for generalizations about the incorporation of maintenance management into contract maintenance.

Assuming that a plant owner will have a maintenance management system similar to the one recommended in Appendix A contained in a plant manual, the basic parts of the system can be expanded for adaptation in a maintenance contract.

It is submitted that the expanded system would have six basic parts as follows:

(a) the equipment configuration list;
(b) the maintenance procedures;
(c) the preventive maintenance cycle schedule;
(d) the recordkeeping system;
(e) the work input control system;
(f) the maintenance data feedback system.

The equipment configuration list, which is a complete inventory of all plant components, will tell the prospective contractor what he will be required to maintain should he be the successful bidder. The maintenance procedures tell him how he will be required to maintain the plant. The preventive maintenance cycle schedule tells him when he is to maintain each component in the plant. The recordkeeping system tells him the administrative procedures he is to follow. The work input control system tells him the owner's policy in work scheduling. The maintenance data feedback system tells him if deficiencies exist in his management of the system.

Each of the elements listed contributes to the owner's goal of programmed routine management decisions and reduced opportunity for autonomous contractor decisions. Although this adds to the owner's protection it does not remove the contractor's uncertainties associated with un-

known corrective maintenance and repair requirements. Through an analysis of the specifications contained in the maintenance management system, the contractor can obtain the information necessary to quantify the contract requirements in terms of labor, materials, and overhead for all requirements except those of corrective maintenance and repair. The owner must also provide the information necessary for the contractor to produce an a priori estimate of corrective maintenance and repair effort.

Most maintenance management systems require that corrective maintenance work be scheduled within the limits of budgetary constraints on the basis of priorities established by maintenance policy.(34, 35) An examination of the philosophy underlying this concept indicates that it is designed to optimize the decision maker's measure of effectiveness, or his objective function, within the constraints set by the budget. In this context, most maintenance management systems' scheduling elements are heuristic optimization procedures. To the extent that these elements are optimization procedures, their formalization and specification in a complete CM contract can be accomplished through the use of operations research methods. That is, the owner's scheduling problem can be observed and formulated and then a scientific (mathematical or heuristic) model can be constructed that attempts to abstract the essence of the real

problem.

It is asserted that it is in the owner's best interests to adopt the "budget" and optimization concept for scheduling work in the complete CM contract. The validity of this statement is supported by the fact that most maintenance management systems utilize this concept in work input control. It is further asserted that due to the large cost in time and effort necessary to develop a mathematical optimization model for the maintenance of a complex plant, heuristic procedures should be adopted. According to Hillier:(36)

> "...in addition to considering the composite measure of effectiveness in the model, one should also consider the cost of the study and the disadvantages of delaying its completion, and then attempt to maximize the net benefits resulting from the study. In recognition of this concept, operations research teams occasionally use only 'heuristic' procedures (i.e., intuitively designed procedures that do not guarantee an optimal solution) in order to find a good 'suboptimal' solution. This is especially the case when the time or cost required to find an optimal solution for an adequate model of the problem would be very large."

The adoption of the "budget" and optimization concept for work input control would require that the owner design a heuristic decision model that would be used to determine the relative measure of effectiveness of each job being considered for work input. In determining how much work to schedule the contractor must consider the limited amount of

labor and materials, as dictated by the owner-established "budget", that can be allocated for that purpose. Thus, the limits of labor and material act as constraints in the contractor's decision process. Since the constraints relate directly to the extent to which the owner's measure of effectiveness can be optimized, the owner must decide how restrictive he can afford to be in this area and establish finite labor and material limits to be used as the constraints.

In this regard, the owner must establish a "budget" for corrective maintenance and repair and from this "budget" the contractor can prepare an exact estimate of his effort necessary to fulfill the "budget" requirements. By establishing a "budget" for corrective maintenance the owner removes contractor uncertainties as to how much labor and material he must allocate to corrective maintenance during the contract period. The owner must communicate the scope of the labor and material limits through the contract document and integrate the limits into the work input control element in the maintenance manual.

It is now appropriate to develop a clear understanding of the role of preventive maintenance inspections in the overall maintenance management system and how the owner can ensure that the contractor diligently pursues this important control function.

3.3 The Preventive Maintenance Inspection System

Maintenance is the function of sustaining or restoring equipment so that the equipment performs its intended job safely, effectively, and economically. Maintenance may be broken down into two basic types:

(a) preventive - periodic tasks of care and inspection scheduled to prevent a breakdown or prolong the life of equipment; and

(b) corrective - unscheduled tasks required to restore equipment to operational status after a breakdown or impending failure is discovered and scheduled tasks including complete disassembly and reconditioning to like-new status.

Preventive maintenance, then, consists of two tasks: inspection and equipment care. Examples of inspection tasks include looking or listening for wear or malfunction, checking out electrical circuits, looking for cracks and tightness, measuring clearance, and looking at corrosion protection. Examples of equipment care tasks include lubricating, renewing seals and packing, adjusting equipment, sharpening cutting edges, replacing worn parts, renewing corrosion protection, restoring worn areas to an acceptable tolerance, and exercising seldomly used units.

The preventive maintenance (PM) inspection and care tasks are programmed in the maintenance management system and can be quantified in terms of the labor and material necessary to carry them out. In most cases, it is through the PM inspections that corrective maintenance requirements are determined and subsequently quantified in terms of the labor and materials necessary to correct the noted deficiencies. The two tasks of preventive maintenance, then, play a central role in the overall purpose of maintenance management. The equipment care tasks act to prevent breakdowns and the inspection tasks give an early indication of corrective maintenance requirements that call for management decisions.

Repeating that maintenance management is a management decision making process, the importance of PM inspections in facilitating this decision process is readily seen. Without the PM inspections, many conditions in the plant environment calling for maintenance decisions may not be discovered. If the contractor, acting as the owner's agent, does not look for and discover encroaching maintenance requirements in the plant, the high ideals of the owner's maintenance management program are unfulfilled.

How does the owner ensure that the contractor will pursue the PM inspections as required by maintenance management fundamentals? In a limited sense, this question indi-

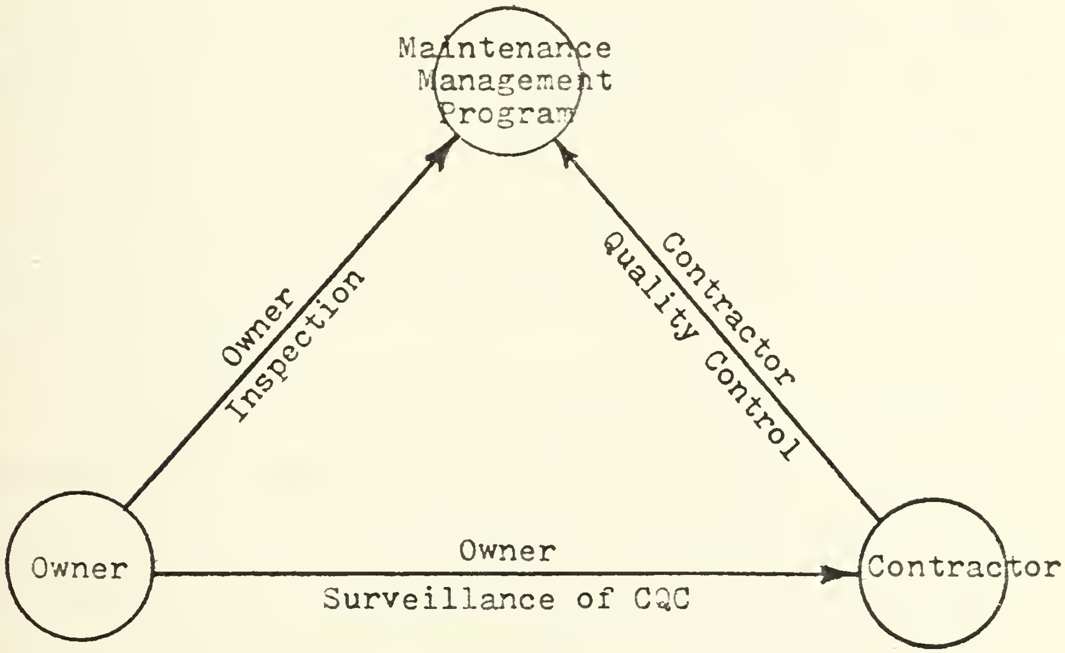
cates a need for contractor quality control. Through the maintenance management system, the contract performance specifications call for the performance of systematic PM inspections and maintenance procedures. The contractor has the responsibility to manage his own inspection program and present to the owner evidence of those inspections that comply with the contract specifications. The owner must institute a contractor quality control program to ensure that the contractor fulfills these responsibilities and to enforce the provisions of the contract specifications.

The U.S. Navy has developed a formal system of Contractor Quality Control (CQC). According to the Navy,(37) the CQC program "encourages a marriage of contractor and government effort to achieve an acceptable facility in accordance with the contract documents rather than a simple shifting of government effort to the contractor." The essence of the CQC system is that it obliges the contractor to prepare a quality control plan prior to initiating the contract. Wittschiebe(38) reports:

> "...the quality control plan is really no more than the formalization of the contractor's own management system that the contractor should use to do the job right once...We will maintain surveillance of the contractor's operations. We will not pay for construction that is in non-compliance with the plans and specifications. The contractor has but to live up to the fundamentals of his quality control plan to be able to see the danger of non-compliance before it takes place and prior to the Navy's knowledge."

Experience with CQC system contract administration at the Public Works Center, Newport, Rhode Island, indicates that the CQC system works very well.(39)

Although the Navy's CQC system has been developed primarily for use in construction contracts, it can be seen through minor extrapolations from the system that complete CM contracts could be accommodated within the system's capabilities. The Navy's CQC system revised for complete CM contracts may be described as having three elements: contractor quality control (CQC); owner inspection; and owner surveillance of the CQC program. Figure 2 provides a graphic view of the relation of each element to the other.



Elements of the CQC System

Figure 2

The contractor quality control element can be implemented in the complete CM contract by including a clause that requires the contractor to periodically provide certified documentation that all inspections required in the PM inspection program during that period were performed. According to the Navy:(40)

> "The contractor has the responsibility to inspect his own work and present for Navy acceptance only such work that complies with the contract plans and specifications. The CQC element establishes contract requirements whereby the contractor is required to provide significant and specific inspection and documentation to satisfy both himself and the Navy that work being performed meets the requirements of the plans and specifications."

The owner inspection element is merely an owner review of the certified contractor inspection reports against the PM inspection schedule to ensure compliance before making any progress payments on the contract. This element can be implemented in the complete CM contract by including a clause requiring owner inspection of contractor reports prior to payment.

The owner surveillance element is an informal liaison between the owner or the owner's contract administration representative and the contractor's CQC representative. This liaison keeps the owner informed of the adequacy of the contractor's maintenance management capabilities and the level of maintenance in the plant. The Navy describes Navy surveillance as follows:(41)

> "Navy surveillance of the CQC element of the program is the means by which the Navy assures itself that the Contractor Quality Control Program is functioning properly. It is through surveillance that the Resident Officer in Charge of Construction (ROICC) is able to determine and adjust the degree of Navy Inspection that is required and applied to a particular project."

It is pointed out that CQC alone can in no way ensure the owner that the contractor's maintenance management efforts will be of adequate "quality" to protect his interests. CQC can, however, hold the contractor accountable for providing the "quantity" of maintenance management effort called for in the contract. In order to ensure adequate quality of maintenance management the owner must provide an "honest reward structure" to the contractor that relates contractor incentive to maintenance effectiveness. A discussion of honest reward will be provided in Chapter 6.

Through the application of CQC and honest reward principles described above, the owner maintains a degree of control over the contractor performance of PM inspections in that the owner has tangible evidence that the inspections are actually being performed. This evidence is provided through certified copies of PM inspection reports. Through the CQC and honest reward system the contractor has a positive incentive to diligently perform the PM inspections since failure to do so would delay progress payments and reduce his profits and false certification of the reports would constitute fraud.

The performance of the owner's PM inspection schedule is assured through the CQC and honest reward system. The outcome of the PM inspection schedule is the determination of plant defects that will subsequently require corrective maintenance or repair. In order to ensure that the magnitude and quality of materials and labor necessary to fulfill the requirements are estimated, the owner must specify that the contractor plan and estimate all maintenance requirements derived from the PM inspection schedule.

3.4 Planning

The purpose of planning and estimating work generated through the PM inspection process is to provide the maintenance decision maker with a continuous indicator of plant maintenance requirements and to provide a systematic basis for workers to prepare for job accomplishment. According to McGuire:(42)

> "Systematic maintenance job planning will control the more critical elements of maintenance work decision making...Maintenance job planning provides the maintenance worker with an understanding of the work and enough information to go directly to the job site with the required materials and tools."

Figure 3 illustrates the various steps that the contractor must follow in planning a job. A review of Figure 3 identifies several steps that call for decisions by the contractor's maintenance job planner. The decision making steps include

the following:

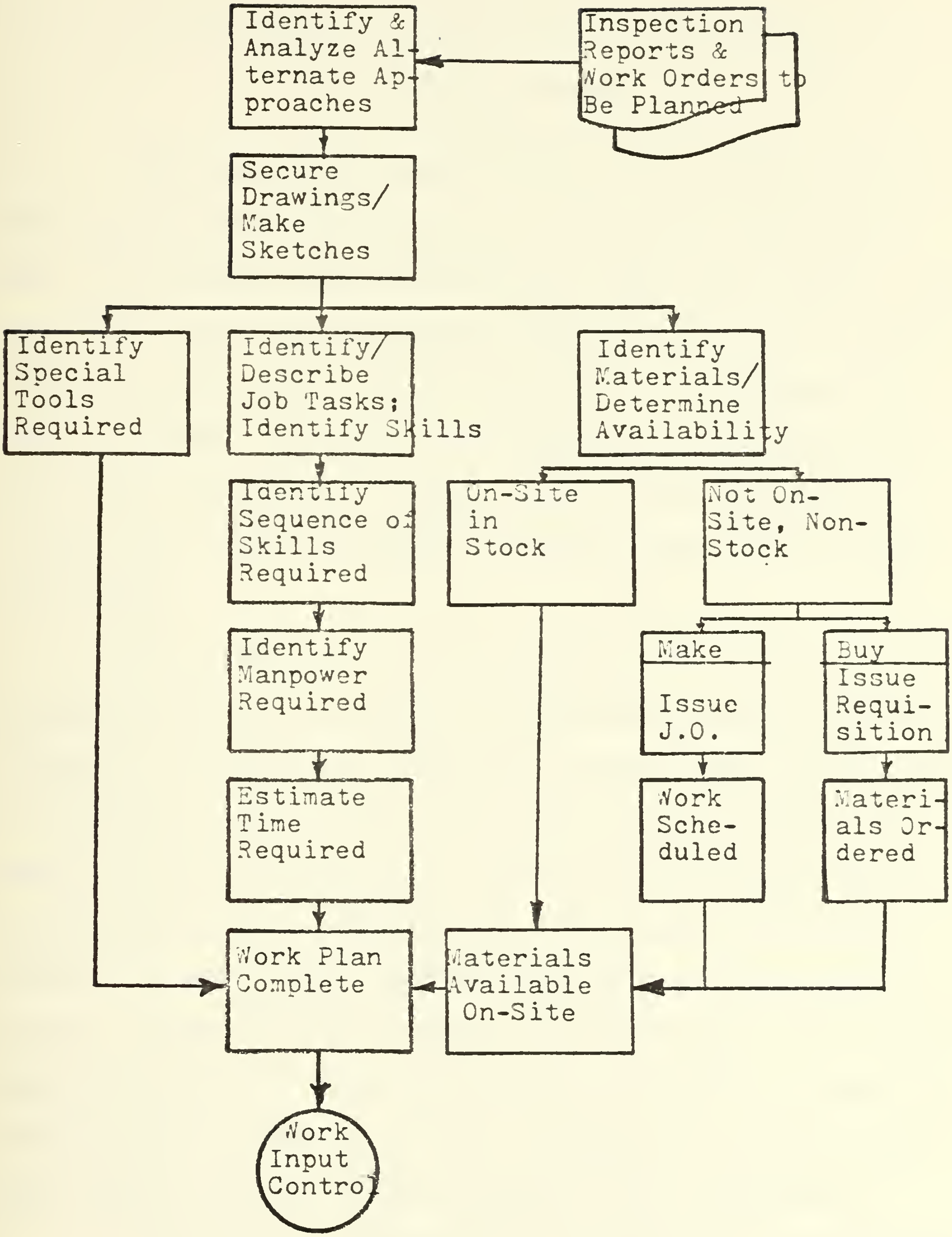
(a) secure drawings and make sketches if appropriate;

(b) identify and describe job tasks;

(c) identify materials required for tasks; and so on.

In the complete CM contract, the owner must program these steps in order to reduce the opportunity for autonomous contractor decisions. Obviously, to program design and material selection decisions, a data base of standard design plans and material specifications must be available.

This goal can be accomplished by specifying in the contract that all repairs and replacements of plant components will be in accordance with the existing as-built design plans and all replacement materials will be provided in-kind as specified by the manufacturer's literature unless written approval for an exception is provided by the owner. Thus, the owner makes it clear that deviations from or revisions to the as-built plans and the use of substitute materials are not acceptable unless he approves of the changes. The standardized plans and material specifications contribute to the owner's protection and help ensure that contractor decisions are in the owner's interests.


Identify & Analyze Alternate Approaches
Inspection Reports & Work Orders to Be Planned
Secure Drawings/ Make Sketches
Identify Special Tools Required
Identify/ Describe Job Tasks; Identify Skills
Identify Materials/ Determine Availability
Identify Sequence of Skills Required
On-Site in Stock
Not On-Site, Non-Stock
Make
Issue J.O.
Buy
Issue Requisition
Identify Manpower Required
Work Scheduled
Materials Ordered
Estimate Time Required
Work Plan Complete
Materials Available On-Site
Work Input Control

Detailed Maintenance Job Planning Chart

Figure 3(42)

3.5 Resource Constraints: Establishing the Decision Boundaries

The inspection element of the maintenance management system generates the plant maintenance requirements and the planning element quantifies these requirements. The next element in the maintenance management process is work input control. Each new job generated is considered for accomplishment along with other jobs previously generated but not accomplished. In this regard, the contractor is tasked with making scheduling decisions that affect plant maintenance.

In Section 3.2 it was asserted that the complete CM contract should incorporate the optimizing scheduling philosophy of maintenance management systems that operate within budgetary constraints. This concept acknowledges that making a priori estimates of total corrective maintenance requirements is not practical but the concept provides a method for approaching optimum performance within subjectively assessed resource limits or constraints (the maintenance "budget"). The term resource constraints is used because limited resources act as constraints in determining the optimum quantity of maintenance work to schedule.

In order to implement this concept in a complete CM contract the owner must decide what the constraints should be and establish them as direct material and direct labor

limits. The quantification of the limits should be based on the owner's prior knowledge of the plant and his assessment of the anticipated contractor risks involved if the limits are too low. The communication of the limits to the contractor establishes the decision boundaries within which the contractor must operate to optimize maintenance effectiveness. In this regard, it is incumbent upon the owner to establish the criteria that determines optimization and provide the necessary incentives to the contractor to vigorously pursue the optimization goal within the constraints. An in-depth discussion of these concepts is provided in Chapters 4 and 5.

The discussion above implies that the contractor will be tasked with maximizing (optimizing) an owner established measure of effectiveness within labor and material budgetary constraints which are also established by the owner. The logical extension of this concept demands that the contractor's compensation for his services be directly related to the extent to which he succeeds in maximizing the measure of effectiveness established by the owner, i.e., the contractor is rewarded or penalized according to the extent of his success or failure. The implication of this extension is that the contractor must perceive a certain amount of risk in assuming the responsibility for performing within the constraints since some of his compensation is related to

his success in this area. It is therefore incumbent upon the owner to minimize the risk to the contractor by limiting the variance of the magnitude of corrective maintenance jobs that the contractor must fulfill.

It is asserted that contractor risk can best be minimized by creating certain mechanisms within the contract that help reduce uncertainties about unknown corrective maintenance requirements. It has been submitted that the contractor uncertainty pertaining to total corrective maintenance and repair requirements can be reduced by establishing a "budget" (resource limits) within which the contractor is to optimize plant maintenance. Uncertainty involving catastrophic failures of plant equipment can be minimized by placing a limit on the magnitude of jobs for which the contractor is held responsible. Uncertainty involving the owner's measure of effectiveness and the contractor's responsibilities in making determinations in this area can be minimized by introducing a work input control decision model that subjects the selection of alternatives process to owner criteria and reduces the need for the contractor to make autonomous decisions.

Three mechanisms can be conceptualized as follows:

(A) The first mechanism may consist of the maintenance management program and the "budget". This mechanism would provide the quantitative information necessary for

the contractor to prepare a bid or proposal to do the work. The maintenance management program would be contained in the plant manual. The "budget" could be presented by the owner as two bid items in the contract document. Bid item one could specify a limited (but explicit) number of manhours of direct labor to be used in fulfillment of corrective maintenance items. Bid item two could specify a limited (but explicit) amount of direct materials (dollar value) to be used in fulfillment of corrective maintenance items. Use of the bid item concept to establish a unified basis for contractor bids on complete CM contracts has had recent practical application.(43)

(B) The second mechanism may consist of a procedure in the work input control element that subjects all work generated and planned through the two previous elements to a threshold evaluation. The purpose of the threshold evaluation is to screen out all jobs greater than a certain magnitude and submit these jobs to the owner for action. It is incumbent upon the owner to establish the threshold limits that he considers reasonable in minimizing contractor risk. The U.S. Navy uses a limit of $25,000 for repair projects to be submitted by the activity commanding officer for funding and performance by others.(44) This converts to about 1000 manhours of direct labor and $8000 in direct materials.

The result of the second mechanism is that it relieves the contractor of the responsibility for work of catastrophic scope that would use up much or all of the corrective maintenance "budget" in single jobs. Since it is not in the owner's interest that jobs should be allowed to become large enough to be rejected in the threshold evaluation, a deterrent to possible contractor profit maximizing behavior in this area should be provided. The contract should state that neither the contractor nor any of his subsidiary companies may bid on the resultant work.

(C) The third mechanism may consist of a resource allocation procedure in the work input control element that subjects all work that passes the threshold evaluation to a decision test that incorporates owner preferences and maintenance policy. Through the work input control decision model, the contractor can make a determination of which maintenance jobs of the group being considered will provide maximum maintenance effectiveness as measured by the owner's preferences. Accordingly, those jobs showing the highest measure of maintenance effectiveness will be scheduled to the extent possible within resource constraints.

In summary, a complete CM contractual framework has been proposed that integrates the accepted concepts of maintenance management, optimization within budget constraints, and the limitation of requirements variance to reduce risk.

The elements of maintenance management provide the medium through which routine maintenance decisions are programmed, thus reducing the opportunity for autonomous contractor decisions and establishing a systematic basis for generating, planning, and accomplishing work. The budget element establishes the decision boundaries within which the contractor must operate to optimize maintenance effectiveness, thus reducing contractor uncertainty as to the total scope of the contract. The limited variance element establishes the maximum limit of magnitude on any particular job that the contractor must perform, thus it reduces the contractor's uncertainty pertaining to his responsibility in recovering from possible catastrophic failures of plant equipment.

Through the framework proposed the contractor can assess the quantity of effort and risk that he must assume in performing the contract requirements. The elements of the contract assure the owner that the plant maintenance requirements will be continuously generated and planned with minimum risk to the contractor. The artificial "budget" introduced into the contract through bid items places constraints on the resources that can be allocated to the goal of optimizing maintenance effectiveness. With this in mind, it is appropriate to determine what criteria establishes optimization and how contractor judgements can be used in fulfillment of the owner's interests.

4.0 WORK INPUT CONTROL: CONTRACTOR DECISIONS VERSUS OWNER INTERESTS

4.1 A Choice Among Alternatives

The use of the work "complete" in complete CM implies that the owner relegates to the contractor the responsibility for work input control as well as the other elements of maintenance management. In maintenance management systems that are constrained by limited resources allocated for corrective maintenance and repairs, work input control is the act of periodically selecting for accomplishment a limited number of jobs from the overall backlog of jobs so as to achieve optimum maintenance effectiveness. The magnitude of work that can be input at any time depends on the magnitude of the corrective maintenance budget.

In the context of the complete CM contract, the corrective maintenance "budget" is established by the magnitude of direct materials and labor specified by the owner in the contract bid items. Work input control in complete CM is the act by the contractor of selecting for accomplishment those jobs that will optimize maintenance effectiveness within the "budget" constraints set by the owner. In this regard, work input control is a decision problem under uncertainty whereby the contractor is tasked with subjectively assessing the relative utility of each alternative

maintenance job pertinent to maintenance optimization and selecting the jobs with the greatest utility for accomplishment.

It is in the assessment of utility by the contractor that much of the ambiguity of complete CM arises. The contract is for the maintenance of the owner's plant, not the contractor's. Therefore, the utility assessment should be a measure of the owner's utility for each job, not the contractor's. Repeating Martin's concerns:(13)

> "...Can we permit a contractor to make economic decisions for us regarding parts and schedules, and can we retain maintenance management personnel sufficiently knowledgeable on all technical details of a contract operation to protect the agency's interests? The career service public employee must live with and be responsible for the results of his decisions, but most contracts are for fairly short periods."

In order to overcome this ambiguity, the owner must inject the various attributes of his personal utility into the work input control decision element.

4.2 A Decision Theoretic Approach

The above analysis restates the need for the owner to maintain a measure of control over the work priority and scheduling process in order to protect his interests. The scheduling process is that of making a choice under uncertainty from a set of alternatives in order to achieve an optimal solution. In this regard, the scheduling process

poses a decision problem in which a "satisficing"(45) or suboptimal solution can be achieved through the use of decision theoretic principles. Just as acceptance of the principles of maintenance management is axiomatic in the plant maintenance arena, the principles of decision theory play a central role in the decision processes of management systems.

Evidence of the use of decision theoretic principles in decision making dates from the pre-revolutionary war period. Consider the following letter from Benjamin Franklin to Joseph Priestley, the discoverer of oxygen, who had asked Franklin's advice on whether or not to accept a new position:(46)

> "In affairs of so much importance to you, wherein you ask my advice, I cannot, for want of sufficient premises, counsel you what to determine; but, if you please, I will tell you how.
>
> "When these difficult cases occur, they are difficult, chiefly, because, while we have them under consideration, all the reasons--pros and cons--are not present to the mind at the same time. Hence the various purposes or inclinations that alternatively prevail, and the uncertainty that perplexes us.
>
> "To get this over, my way is to divide half a sheet of paper by a line, into two columns; writing over the one "pro" and over the other "con". Then, during three or four days' consideration, I put down under the different heads, short hints of the different motives that at different times occur to me for or against the measure.
>
> "When I have then got these together in one view, I endeavor to estimate their respective weights, and, where I find two (one on each side) that seem equal, I strike them both out.

> If I find a reason "pro" equal to some two reasons "con" I strike out the three. If I judge some two reasons "con" equal to three reasons "pro", I strike out the five; and thus proceeding, I find, at length, where the balance lies; and if, after a day or two of further consideration, nothing new that is of importance occurs on either side, I come to a determination accordingly.
>
> "And, though the weight of reasons cannot be taken with algebraic quantities, yet, when each is thus considered separately and comparatively, and the whole lies before me, I think I can judge better, and am less liable to make a rash step; in fact, I have found great advantage from this kind of equation in what may be called moral or prudential algebra.
>
> "Wishing sincerely that you may determine for the best, I am ever, my dear friend,
>
> Your most affectionately,
>
> Benjamin Franklin"

Franklin declined to advise Priestley "...for want of sufficient premises", i.e., Franklin did not know the quality or relative weights of the attributes that comprised Priestley's utility for the outcome of the alternate acts. Instead, Franklin proposed a decision matrix in which each of the important attributes of Priestley's utility relative to the decision problem were to be listed. Additionally, the matrix was to be formulated in such a way that the utility of each act relative to the attributes could be measured in terms of "pro-ness" and "con-ness" as determined by Priestley.

Implied in Franklin's advice is the notion that if Priestley could determine the relative weights of all of the attributes important to him, he could reformulate those attributes so that each was equal in weight to the next and list them. If Priestley had formulated his decision problem as an equal-weight attribute matrix and entrusted Franklin to assign the relative "pro-ness" and "con-ness" for each attribute, would Priestley's interests have been served? This concept is relevant to the plant owner's decision problem and bears upon the viability of applied behavioral models in decision making.

Bowman(47) asserts that viable decision rules can be formulated to create programmed decisions on production scheduling based on the manager's past behavior. Research was performed by Bowman to determine if behavioral models could provide decisions superior to the decision maker's own decisions. It was found that behavioral models gave results superior to decision makers in all cases examined. By way of explanation as to why decision rules derived from management's own average behavior might yield better results than the aggregate behavior itself, Bowman states:(48)

> "Man seems to respond to selective cues in his environment--particular things seem to catch his attention at times (the last telephone call), while at other times it is a different set of stimuli. Not only is this selective cueing the case, but a threshold concept seems to apply. He may respond not at all up to some point and then overrespond

> beyond that. It is this type of behavior which helps explain the variance in the organization's (or its management's) behavior."

Bowman's research shows that the behavioral model approach to scheduling can be superior to the individualistic approach of management. Additional support for this approach is given by Simon who states:(49)

> "For the operations research approach to work, nothing has to be exact--it just has to be close enough to give better results than could be obtained by common sense without the mathematics."

It is reasonable to assert, then, that the plant owner can approach a solution to his decision problem by creating a behavioral or heuristic model in the form of a decision matrix that includes the many attributes of his personal utility for plant maintenance and inserting this model into the work input control element of the contract. It is implied in this approach to work input control that the contractor assumes the role of expert assessor for the owner to assess the relative utility of each job measured within the owner's utility attributes. To understand how the owner may frame his decision matrix in such a way as to ensure that contractor judgements are in his best interests, it is appropriate to discuss utility theory.

Pratt, et. al.,(50) develops a theory of utility and choice based on the following assumptions:

(A) Basic assumption 1 - existence of a canonical* basis:

> "Suppose the decision maker prefers prize W to L. Given any positive integer N, the decision maker can imagine an experiment with N possible outcomes such that, if one lottery entitled him to prize W contingent on the occurrence of one of n_1 possible outcomes and L otherwise while another lottery entitles him to prize W contingent on the occurrence of one of n_2 possible outcomes and L otherwise, he will prefer the former lottery to the latter if and only if $n_1 > n_2$."

(B) Basic assumption 2a - quantification of preference:

> "Given any decision problem with any set of possible consequences, the decision maker can select a consequence c^* which he finds at least as attractive, and another consequence c_* which he finds at least as unattractive, as any of the possible consequences; and he can then quantify his preference for any possible consequence c by specifying a number $\pi(c)$ between 0 and 1 inclusive such that he would be indifferent between (1) c for certain, and (2) a lottery giving a canonical chance $\pi(c)$ at c^* and a complementary chance at c_*."

(C) Basic assumption 2b - quantification of judgement:

> "Let θ_0 be any real-world event, and let c^* and c_* be the consequences defined in basic assumption 2a. The decision maker can quantify his judgement concerning θ_0 by specifying a number $P(\theta_0)$ between 0 and 1 such that he would be indifferent between (1) the right

---

*All possible outcomes are regarded as equally likely by the decision maker. If N balls are placed in an urn and n of the balls are red then the canonical chance of selecting a red ball is n/N.

> to receive c* if θ_0 occurs, otherwise c_*, and (2) a lottery giving a canonical chance $P(\theta_0)$ at c* and a complementary chance at c_*."

(D) Basic assumption 3 - transitivity:

> "Let l', l'', and l''' denote any three lotteries. If the decision maker has any preferences among these lotteries, then these preferences should be transitive in the sense that for example:
>
> (a) if he is indifferent between l' and l'' and between l'' and l''' then he is indifferent between l' and l''';
>
> (b) if he is indifferent between l' and l'' but prefers l'' to l''', then he prefers l' to l''', and so forth."

(E) Basic assumption 4 - substitution of prizes:

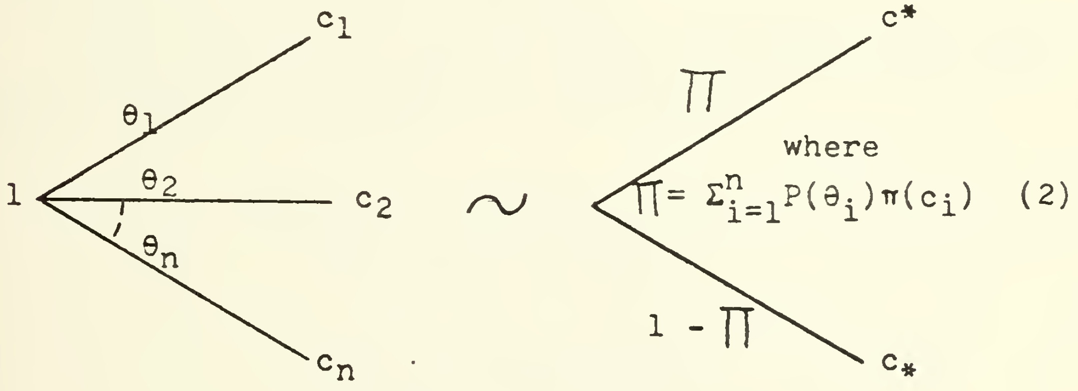
> "Let a lottery be modified by replacing just one of its prizes with another. If the decision maker is indifferent between the original and new prizes, he should be indifferent between the original and modified lotteries."

Decision problems normally call for a choice among several acts when the consequence of one or more of these acts depends on which one of a set of possible events occurs. Using the Pratt assumptions as a basis, it is reasonable to assert that the decision maker must make two sets of preliminary evaluations in order to approach a solution to the problem. He must on one hand quantify his judgements about the possible events by assigning to each event θ_i in a mutually exclusive and collectively exhaustive list $\theta_1, \ldots, \theta_i, \ldots, \theta_n$ a judgemental probability $P(\theta_i)$. He

must on the other hand quantify his preferences among consequences by choosing appropriate reference consequences c^* and c_* and then assigning to every consequence c_i a number $\pi(c_i)$ such that he would be indifferent between c_i for certain and a lottery giving a canonical chance $\pi(c_i)$ at c^* and a complementary chance at c_*. Given the assessments $P(\theta_i)$ and $\pi(c_i)$ it is readily seen that the value or weighted preference of each act can be computed:(50)

$$\Pi = \Sigma_i \, \pi(c_i)P(\theta_i) \tag{1}$$

Capital pi (Π) exhibits the canonical chance that the decision maker would take in order to get the prize c^* with a complementary chance at c_*. This concept can be illustrated as follows:



where

$$\Pi = \Sigma_{i=1}^{n} P(\theta_i)\pi(c_i) \tag{2}$$

Real lottery

Simple canonical lottery

Clearly, the concepts of c^* and c_* are introduced to overcome the inability of the decision maker to attach cardinal utility to a consequence. c^* and c_* establish a basis for ordinal preference ordering of consequences through what Thompson(51) calls a "preference yardstick". In this regard, c^* is assigned the value 1 (the top of the yardstick) because it is at least as good as any of the possible consequences anticipated. The value 1, then, is an ordinal value signifying that a consequence is as good as the best.

Since these values are ordinal, then their relative standing cannot be changed by adding to or multiplying their values by a positive constant or constants. In this regard, Pratt(52) asserts that utilities are "indifferent up to a linear transformation", i.e., their relative standings will not be changed by a linear operation.

Assume that the decision maker's utility for a consequence c_i can be expressed as follows:(50)

$$u(c_i) = a + b\pi(c_i), \text{ then,}$$

$$\begin{aligned} U &= \Sigma_i u(c_i)\ P(\theta_i) \\ &= \Sigma_i \left[a + b\pi(c_i) \right] P(\theta_i) \\ &= a\ \Sigma_i\ P(\theta_i) + b\ \Sigma_i \pi(c_i)\ P(\theta_i) \\ &= a + b\,\Pi \end{aligned} \tag{3}$$

a and b are positive linear transformations and Π is a utility function. Since it involves the application of the

judgemental probability, $P(\theta_i)$, Π is the "expected" utility of the act or lottery considered.

Arrow(53) asserts that utilities can be summed and averaged. If Π can be determined for each attribute of a decision maker's personal utility pertaining to a choice among alternatives, then it follows that the sum of Π's across the attributes for each alternative will provide an index of the decision maker's aggregate utility for that alternative. From this statement it becomes apparent that if a decision maker can list the attributes that make up his personal utility for an act and for each of the attributes evaluate the preference for consequences and probability of occurrence of events resulting from the act, then his expected utility for the act can be computed.

The two aspects discussed above that speak directly to the decision maker's utility are (a) the attributes within which the aggregate utility is measured and (b) the preference for consequences of possible events stemming from each alternate act. The subjective probability aspect of the decision maker's utility merely "weights" it, i.e., converts it to expected utility. Since the plant owner's goal is to inject his personal utility into the work input control element, it appears that one way would be to segregate the attributes and preference aspects from the subjective probability aspect and program the two former aspects into a decision matrix for work input control.

With the proper incentives to engender honesty, the subjective probability aspect of the owner's utility can be left for the contractor's assessment.

In order to program the different attributes of his utility for maintenance into a decision matrix, the owner can develop a multi-attribute utility (MAU) model that defines the various dimensions of his utility framework. Much is written on the eliciting of MAU models from the decision maker. Huber(54) states:

> "Two tasks that decision science consultants are often given are (1) to generate a list of alternatives for top-level decision makers to choose from, and (2) to help these decision makers make choices. In the first case, the consultant wants to be able to develop and screen in alternatives that will be highly valued, and to screen out alternatives that will not. In this case, he attempts to simulate the implicit model that the decision maker actually uses. In the second case he wants to be able to improve the decision maker's evaluation model (and also, of course, the decision process). In this case he attempts to approximate the model that the decision maker wants to use."

It is noted that MAU's are numbers that represent the utility or satisfaction associated with an item, outcome, or alternative having more than one valued property (attribute). Referring to the discussion of utility theory developed earlier it is clear that MAU's are the summation of Π's for each alternative where:(50)

$$\Pi = \Sigma_i P(\theta_i)\pi(c_i) \qquad (4)$$

for each particular attribute. In the context of the plant owner's goal of injecting his utility into the work input control element, the MAU model must be formulated in such a way that the owner's preferences are integrated into the evaluation model.

In the MAU model, preferences appear in two areas: (a) the relative weight or importance attached to each attribute in the MAU model, and (b) the preference for consequences of possible events stemming from the alternate acts. In order to create a model devoid of ambiguity it is important that the preference for each attribute be programmed within the model. MacCrimmon, et.al.,(55) states:

> "To make a rational decision, the decision maker must choose in accordance with his preferences. Since these preferences reside within the head of the decision maker, they are not apparent to an external observer, and they may not be clearly known by the decision maker himself. One practical way to think about these preferences is to express them in terms of trade-offs--the amount of one attribute the decision maker will give up in order to gain specified amounts of some other attribute(s). The locus of trade-offs from a given combination of attribute values generates an iso-preference curve or indifference curve between the attributes. The trade-off or marginal rate of substitution at any point is the slope at that point. Iso-preference curves are contours on a general utility function. An alternative to our approach of focusing on iso-preference curves between attributes is to directly study the utility function. This alternate approach almost always assumes, for practicality's sake, that the utility function is additively separable into utility functions of each attribute."

In this regard, the plant owner must use the "trade-off" concept in establishing the relative weight of each of the attributes in his MAU model. The most straightforward way to accomplish the trade-offs is to establish attributes of equivalent weight. A successful practical application of this concept is reported by Skolnick(56) in a paper describing the Contender Evaluation and Selection Technique (CONTEST) used by the Navy in selecting design and construction contractors. Skolnick states:

> "It has been the consensus that, in very gross terms the measure of a potential contractor can be obtained by the resulting effect of his proposal upon the quality indexes of cost, product performance, and time; indeed even DOD contract people generally agree upon the utility of such a primitive reference frame. It is not possible, however, to distinguish among highly qualified bidders the best for a particular task if such a set of 'spatial characteristics' is employed. As a first step in organizing the matters of importance, the notion of 'Factor' is introduced. In a particular competition the significant Factors might be identified as:
>
> I. Design Factor
> II. Production Factor
> III. System Factor
> IV. Management Factor.
>
> "It should be difficult to make a case, that of the four Factors displayed above, any one is more important than another, either qualitatively or quantitatively, i.e., they should be approximately of equal worth. They are, in reality, an artifice introduced mainly for organizational convenience. If the Factors are then resolved into their basic equivalent components (called Groups in CONTEST), a hyperspace of N dimensions will be produced (where N is the total number of Groups

> assembled under all the four Factors); these N axes cover the entire space of concern and serve as its basis.
>
> "The important point to be recognized is that subjective assessment appraised the Groups under each Factor as equal and, since the Factors themselves were approximately equivalent, it was possible to draw the conclusion that the individual Groups were equal, one to the other. It is extremely difficult to make the argument that a Group under Factor I is equal in weight to a Group under Factor IV otherwise.
>
> "This is not to say that essay-like justification cannot be presented; it merely is acknowledged that Group equality, when the Groups are compared directly, will always be a moot point dependent upon the argumentative inclinations of the critic. For this reason, it is preferable to approach the 'proof' of the Group equality through the logic pattern sketched above. Thus, one first displays approximately equal Factors, then breaks each Factor into approximately equal Groups, and, finally, infers relative Group equality as a consequence of the initial hypothesis."

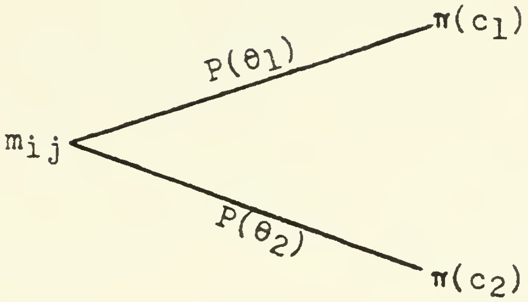
Through the use of the CONTEST "equivalent factor" method of building the owner's MAU model the problem of attribute preference is resolved. The second preference factor, that of preference for consequences, can also be entered into the MAU model with relative ease.

In injecting his preference into the work input control element the owner is interested in ensuring that only those jobs are selected for accomplishment that will optimize his measure of effectiveness, i.e., provide the maximum MAU. Since several alternatives are considered at the same time the simple test of the best alternative is that it is

clearly superior to all of the rest in terms of maintenance effectiveness. A more comprehensive test for each alternative as it would apply to each specific attribute in the MAU model would be "is it clearly superior to the 'norm' of the other alternatives". This test is less restrictive than the first. It is seen, then, that the decision problem is a dichotomy in which the best prize (c^*) is the consequence of the event that maintenance effectiveness improved greater than the average alternative could have provided and the least prize (c_*) is the consequence of the event that maintenance effectiveness did not improve greater than the average alternative could have provided. From the Pratt basic assumption 2a pertaining to utility theory it is clear that the owner's preference for the best prize, $\pi(c^*)$, is assigned the value 1 and his preference for the least prize, $\pi(c_*)$, is assigned the value 0.

Visualize, now, a matrix containing all of the equal weight attributes of the owner's MAU listed along the left side and a sequential listing of all maintenance jobs to be considered for scheduling across the top. Assume that the contractor is tasked with evaluating all alternatives as they apply to each attribute and from this evaluation he is to assess the subjective probability that each particular job is superior to the norm of all the jobs being considered as it applies to each attribute. Clearly from this

exercise all of the elements that make-up the owner's MAU for each job are present for each attribute:



(5)

where $P(\theta_1)$ = probability of superiority

$P(\theta_2)$ = probability of not superior = $1 - P(\theta_1)$

$\pi(c_1)$ = preference for superiority, $\pi(c^*) = 1$

$\pi(c_2)$ = preference for not superior, $\pi(c_*) = 0$

m_{ij} = maintenance job j considered relative to attribute i.

The owner's single attribute utility for m_{ij}, then, is:

$$\begin{aligned} \Pi m_{ij} &= \Sigma_{i=1}^{2} P(\theta_i)\, \pi(c_i) \\ &= P(\theta_1)(1) + \left[1 - P(\theta_1)\right](0) \\ &= P(\theta_1) \end{aligned} \tag{6}$$

Accordingly, the owner's MAU for maintenance job m_j is:

$$MAU_{m_j} = \Sigma_{i=1}^{n} \Pi m_{ij} = \Sigma_{i=1}^{n} P_i(\theta_1) \tag{7}$$

Having determined the MAU for each maintenance job under consideration, the matter of work input control becomes the simple process of selecting the jobs with the greatest MAU

rating for accomplishment within budgetary constraints.

An MAU model has been conceptualized in which the only judgement required of the contractor is the assessment of subjective probability. Chapter 5 will provide a discussion of a proposed means designed to engender honesty on the part of the contractor in his assessment of probability. Contingent upon the development of an honest reward function for the contractor as a probability assessor, it is asserted that the MAU concept previously proposed provides the vehicle through which the plant owner can produce a viable complete CM contract. Accordingly, the autonomous contractor decisions versus owner interests dilemma can be resolved.

4.3 A Multi-Attribute Utility Model

In order to visualize how an MAU model for work input control can be created, it is appropriate to apply the concepts previously developed to an existing CM contract situation and formulate a hypothetical model. Accordingly, the Guantanamo CM contract is considered a good example to use in the analysis because of personal experience with the various aspects of the Guantanamo plant. Brevity requires that the analysis be confined to one segment of the overall plant, therefore, an MAU model will be developed for the complete CM of one 750,000 gallon-per-day seawater evapor-

ator. The purpose of the evaporator is to provide a supply of drinking water and industrial water for the Guantanamo Naval Base. Appendix B provides a description of the processes and components involved in the plant.

Using the CONTEST(57) approach to developing the MAU model the steps to follow are: (a) determine several overall factors of equal weight that define the important attributes of the plant in a general way, and (b) subdivide each factor into a certain number of equal weight groups of detailed attributes that include all attributes considered important for plant effectiveness. Hence, if the groups under each factor are equal in weight one to the other and the factors are all of equal weight then by the Pratt assumption of transitivity each group is equal in weight to any other group, regardless of the factor.

Analysis of Appendix B shows that there are four general attributes of the evaporator under consideration that define its functions:

(a) production;

(b) quality control;

(c) efficiency control; and

(d) corrosion control or reliability.

It is difficult to make a case that any one of these factors is more important to the overall effectiveness of the plant than any other. Therefore, it is reasonable to assume that

the plant owner may be indifferent in his preferences among the four attributes. These four attributes, then, are chosen as the major factors in the CONTEST MAU model.

Proceeding first with an analysis of the components and processes involved in plant production, the following is seen:

(a) energy is boosted in the brine heater;

(b) vacuum is regulated by the air ejector;

(c) distillate is collected in the product trough and replaced by makeup;

(d) the process is contained by the vessel shell.

Each of these functions contributes directly to water production. To facilitate the use of these concepts in the MAU model, they may be posed in terms of the function they serve in production. Within the MAU matrix, these terms may appear as follows:

FACTOR I: Production
  Group A: Energy addition
  Group B: Vessel vacuum regulation
  Group C: Distillate collection and makeup
  Group D: Process containment

Again, the factor of production would fail without the effectiveness of any one of the groups listed. Therefore, it is reasonable to assume that the plant owner may be indifferent in his preferences among the detail attributes

listed.

The next factor to be considered is quality control. The control of quality of the evaporator product water encompasses control of both the carry-over of impurities within the evaporating brine and the contamination of pure product with impure water. A review of Appendix B indicates that carry-over is deterred by an entrainment separator or "demister" screen and the finished product is segregated from the flashing brine by the product trough. The volatility of flashing is deterred by introduction of an "anti-foaming" agent into the brine and heat recovery (seawater) is contained within the heat recovery tubes. Thus, it can be deduced that product water quality is adversely affected by:

(a) brine droplets carrying over with vapor;

(b) flashing brine penetrating the product trough (through holes);

(c) brine volatility flooding entrainment separator (demister); and,

(d) seawater leakage from heat recovery tubes.

For the purposes of the MAU model, each of these deficiencies can be re-expressed in terms of the function that deters their actualization:

FACTOR II: Quality Control

Group A: Product-mist separation

Group B: Product-brine separation

Group C: Brine anti-foaming

Group D: Product-heat recovery water separation

If the evaporator failed in any one of the above functions, product water quality would deteriorate until it would not be fit for human consumption. It can be assumed, then, that the plant owner may be indifferent in his preferences among the four attributes listed.

Next the efficiency factor must be considered. Evaporator efficiency is enhanced through waste heat recovery and chemical recovery. The warm, chemically-treated brine that remains after flashing through the evaporator is recycled through the heat recovery tube bundles to reclaim the latent heat of vaporization from condensing product water. The warm brine is extracted from the last stage of the evaporator by the brine extraction pump and boosted in pressure by the booster pump. The heat recovery tube bundles, "stage separations",(58) and vessel insulation facilitate the recovery of heat by the recycled brine from the condensing product water. The chemical feed systems condition the brine to retard scale formation and maintain heat transfer.

The salient features of efficiency control, then, are:

FACTOR III: Efficiency Control

Group A: Stage separation

Group B: Heat recovery

Group C: Brine recycle

Group D: Chemical feed

A deficiency in any one of the attributes listed above would cause an immediate deterioration in evaporator efficiency. It is therefore concluded that the plant owner may be indifferent in his preferences among the attributes.

The final factor to be analyzed is plant reliability. This aspect involves corrosion control and redundancy for dynamic equipment. The critical dynamic aspects of the evaporator include the pumping of brine, condensate, and product water. The corrosion control aspect involves the degasification (deaeration) of the incoming evaporator make-up water. In terms of reliability, the plant owner should ensure that there are always backup pumps for the pumping of brine, condensate, and product water to allow down time on the primary pumps for preventive and corrective maintenance and to provide for unforeseen casualties. Additionally, corrosion control plays an equally important role because without it many of the plant systems exposed to the highly corrosive salt water environment would deteriorate at a rapid rate.

The important attributes of plant reliability, then, are:

FACTOR IV: Reliability

Group A: Condensate pump redundancy

Group B: Brine pump redundancy

Group C: Product pump redundancy

Group D: Degasification

It is asserted that the sixteen attributes determined above tend to provide a thorough yet realistic definition of the evaporator plant owner's utility structure. The views of Huber in discussing the methods for eliciting MAU models are pertinent:(59)

> "A number of issues remain to be discussed. One concerns the difficulty of selecting the attributes to be included in the model so as to be thorough yet realistic. This is especially important when developing observer-derived models, as the list of possible attributes often has to be pruned to make the cognitive task of responding to multi-dimensional stimuli a reasonable one. On the other hand, if an important attribute is not considered somewhere in the decision process, this could have serious consequences. One can think of many ways to interact with the client in selecting the attributes to be included, but apparently none have been tested for their strengths and weaknesses. Consequently at this point we must be satisfied with simply being aware of the problem. Hopefully, explicit recognition of the issue will help us to avoid any major disasters."

Care was taken at the beginning of this analysis to stress that the opinions and choices of attributes were based on personal experience with the Guantanamo plant. A basic assumption in the development of any MAU model must be that the plant owner is familiar with his plant and can organize his opinions pertaining to plant effectiveness as specified

in the CONTEST method. If the owner is not familiar with his plant, it will be in his best interests to retain a consultant to develop his model.(60)

Integrating the sixteen attributes into a comprehensive whole, Figure 4 provides an illustration of the evaporator MAU model structure.

FACTOR I: Production
  Group A: Energy addition
  Group B: Vessel vacuum regulation
  Group C: Distillate collection
  Group D: Process containment

FACTOR II: Quality Control
  Group A: Product-mist separation
  Group B: Product-brine separation
  Group C: Brine anti-foaming
  Group D: Product-heat recovery water separation

FACTOR III: Efficiency Control
  Group A: Stage separation
  Group B: Heat recovery
  Group C: Brine recycle
  Group D: Chemical feed

FACTOR IV: Reliability
  Group A: Condensate pump redundancy
  Group B: Brine pump redundancy
  Group C: Product pump redundancy
  Group D: Degasification

Guantanamo Evaporator MAU Structure

Figure 4

The model can be included in the contract posing the following specifications:

(A) Analyze all jobs passing the threshold evaluation monthly and select a job from among them having the

greatest central tendency as regards its possible beneficial effects on plant improvement in "FACTOR I, Group A: Energy Addition".

(B) Similarly, proceed to select a job with the greatest central tendency in "Vessel vacuum regulation" and so on, through "Degasification".

(C) For each job other than the one with central tendency, consider the effect that accomplishment of this job might have, first, on plant improvement in "energy addition".

(D) Assess the probability that the effect of the job being considered is clearly superior to the possible effect of the job with greatest central tendency on plant improvement in "energy addition", and list the probability in matrix form.

(E) Proceed to assess the probability of superiority of the job being considered in each of the remaining attributes and list the probability in the matrix.

(F) Proceed in a similar manner for all other jobs awaiting work input control.

When complete, the matrix would appear as in Figure 5. Assuming that an honest reward function is included in the contract to provide incentive for the contractor to be honest in the assessment of probabilities, the owner's MAU for each job is found by simply summing the probabilities

for each job across all attributes.

$$\begin{array}{llcl}
\text{FACTOR I} & & & \\
 & \text{JOB } m_1 & \text{JOB } m_2 \;\cdots\cdots\cdots & \text{JOB } m_n \\
\text{Group A} & P_{1,1} & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots & P_{1,n} \\
\text{Group B} & P_{2,1} & & \cdot \\
\text{Group C} & P_{3,1} & & \cdot \\
\text{Group D} & P_{4,1} & & \cdot \\
\text{FACTOR II} & & & \\
\text{Group A} & P_{5,1} & & \cdot \\
\cdot & \cdot & & \cdot \\
\cdot & \cdot & & \cdot \\
\cdot & \cdot & & \cdot \\
\text{FACTOR IV} & & & \\
\text{Group A} & P_{13,1} & & \cdot \\
\text{Group B} & P_{14,1} & & \cdot \\
\text{Group C} & P_{15,1} & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots & P_{15,n} \\
\text{Group D} & P_{16,1} & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots & P_{16,n}
\end{array}$$

Guantanamo Evaporator Work Input Control Model

Figure 5

Simply stated, the concept of ranking each maintenance job according to its MAU establishes its priority. In many existing maintenance management systems, informal MAU models are used to assess work priority. In this regard, the concept of relative ranking by measures of utility

to establish job priority agrees closely with the classical concepts researched by Corsano.(61)

4.4 Scheduling

The assessment of the plant owner's MAU for the maintenance jobs awaiting work input subjectively establishes the "expected" ranking of each job in its effect on optimization of plant performance. Repeating that the contract has implemented the "optimization within budgetary constraints" concept, scheduling becomes the act of selecting for accomplishment the jobs with the highest MAU ratings (priority) to the extent possible within the constraints set by the "budget".

In many maintenance management systems a "work input control" schedule or "shop load plan"(62) is prepared on a monthly basis with more detailed "shop" schedules(63) prepared on a weekly basis. Work enters the shop load plan with "expected" material and manpower availability dates and then is moved to the shop schedule when materials and manpower are actually available. The shop load plan, then, must allow for material lead times and unscheduled manpower requirements.

The material lead time factor is a critical one for the plant owner in preparing a complete CM contract. Since the owner is purchasing a total service from the contractor,

including material coordination, allowance must be made for material lead time to ensure that all materials ordered are on-board prior to the conclusion of each contract period, and similarly, that enough material is always on-board to keep the corrective maintenance forces employed. In this regard, it can be expected that the "mean" lead time for materials used in a plant will be about 90 days. The owner must ensure that at least enough materials are on-board at the beginning of each contract period to last for 90 days and that all resources earmarked for material procurement are obligated, say, 120 days before the end of each contract period. The initial 90 day factor is necessary to keep corrective maintenance forces employed until long-lead materials arrive and the 120-day factor is necessary to ensure that all materials are on-board prior to contractor demobilization if he does not get subsequent years' contracts.

Accordingly, the owner should specify the rate at which the contractor is to expend the resources specified in the contract bid items for corrective maintenance. As a general rule, the owner may want to specify that one-twelfth of the budget component for manhours of direct labor be scheduled at the beginning of each month starting with the initial month of the contract period and continuing through all twelve months (assuming a one-year contract).

On the other hand, the direct materials component of the budget should be expended at the rate of one-eighth per month beginning with the first month and continuing through the eighth month's schedule.

The shop load plan, which is prepared at the beginning of each month, is actually a projection of the long range plant requirements. Much of the work on the shop load plan is projected for 90 days with some as much as 6 months away. In this regard, work entered on the shop load plan by the contractor during the seventh and eighth months of the contract period is projected into the next contract period. Scheduling during the ninth through twelfth months will be "shop" scheduling because the material budget is obligated by the eighth month. Since materials for the projected work should be on-board by the beginning of the next contract period, the work plan, the schedule, and the material availability are the basis for an explicit performance specification for the first 90 days of the subsequent year's contract. This work meets the classical conditions established for contractual procurement:(64)

(a) it is identified by measurable units;

(b) it is estimated in advance;

(c) it is described in a job plan; and

(d) it is scheduled.

The contract forces mobilize with 90 days of work scheduled

and demobilize with all materials ordered during the contract period staged on-board. It is important that the owner delay the final month's progress payment to the contractor until all materials are on-board in case discrepancies arise. This function should be an integral part of the contractor quality control element described in Section 3.3.

Based on the requirement that 90 days of work be scheduled at the beginning of the contract period and the material budget be obligated by the eighth month, it is seen that the first contractor shop load plan (in January) will project work beginning in April and ending the second week in May. Similarly, the February shop load plan will project work from mid May until the beginning of July, and so on, until the August shop load plan will project work until the end of March of the following year.

Work generated through inspections during August through December will be backlogged for consideration in the preparation of the January shop load plan by the subsequent year's contractor.

An important attribute necessary for a flexible scheduling system is that it must accommodate emergency work. The term "emergency work" implies (a) that it takes priority over other work being performed, and (b) that it must be accomplished immediately. The fact that a job is an emergency implies that it was not detected through the

preventive maintenance inspections soon enough to correct the deficiency before it became an emergency and it therefore indicates the limitations of human inspectors.

There would be no ambiguity, then, if the owner specified that the contractor determine emergency work and circumvent the scheduling procedure to immediately schedule such work. The procedure of circumventing the scheduling procedure simply says that the emergency work has a probability of 1 that it is "clearly superior to norm" in each of the owner's MAU attributes and that it would have been scheduled earlier if it had been detected earlier. In this regard, the contractor is following the MAU model in the work input control element since he is assigning a probability of 1 to "clearly superior to norm" in a virtual sense. To the extent that the contractor is assigning a virtual probability to the various attributes in the owner's MAU model for the emergency work, he will be subject to incentives to be honest in his assessment of probability as dictated by any reward structure that may be introduced into the contract by the owner.

It is now appropriate to discuss how the owner can develop an honest reward structure for the contract.

5.0 A NATURAL IMPUTED REWARD STRUCTURE

5.1 General

The contract framework developed in the previous chapters provides many controls and safeguards that tend to protect the owner's interests in plant maintenance. However, unless the owner adequately deals with the issue of how to engender honesty on the part of the contractor in his efforts in all areas of maintenance management in general and his assessment of MAU probabilities in particular, the owner's interests cannot be fully protected.

It is desired that the contractor report the MAU probability that he really thinks; he should not play games, nor distort his "true" feelings. For example, he may worry that if he says that the event "superior to norm" has probability $P(\theta_1) = 0.9$, the owner will do some utterly foolish thing, and therefore he might say $P(\theta_1)$ is 0.5 to prevent the owner from doing harm to himself and to society. Or better yet, he might be worried that if he says $P(\theta_1)$ is 0.9 and not θ_1 occurs, then he will be totally discredited; and therefore to hedge against this possibility he might be tempted to say $P(\theta_1)$ is 0.5. No, it is desired that the contractor say what he really believes, therefore, the owner must devise an incentive scheme which will make him tell the "truth".

Savage states:(65)

> "One interesting way to adjust the rewards and penalties of the respondent to the interests of the interrogator...is to give the respondent a fractional interest in the business involved."

It is appropriate, then, that the owner devise a reward scheme for the contractor that will give him a virtual share in the plant. In this way, the contractor's reward is tied directly to the owner's utility and when either one gains, the other gains.

5.2 The Profit Incentive

In order to devise a business sharing scheme for contractor reward it is of interest to analyze the various pricing arrangements normally used in contracting. Although there are many forms of the basic pricing arrangements, the analysis can be facilitated by distinguishing two polar contract types.

At one extreme is the firm-fixed-price (FFP) contract. In this type of pricing arrangement, the contractor promises to deliver to the owner certain goods or services at a price which, after agreed upon by the contractor and owner, is not subject to adjustments reflecting actual costs to the contractor. The profit to the contractor, then, is the agreed upon contract price minus his actual costs.

At the opposite extreme is the cost-plus-fixed fee (CPFF) contract. In this type of contract, the owner and the contractor initially agree upon a fee or profit amount based on an estimate of the contract costs. The cost estimate is not binding; the owner agrees to reimburse the contractor for all allowable expenses incurred in executing the contract. Thus, the "price" in a CPFF contract is flexible, whereas, the fee is fixed. Since the fee is not reduced if the "price" rises it can be said with certainty that the CPFF contract provides a weaker incentive for cost reduction and efficiency than the FFP contract.(66)

All of the financial risk involved when actual costs rise above the agreed upon costs is borne by the contractor in the FFP contract and by the owner in the CPFF contract. In this sense, the two pricing arrangements are polar alternatives. A third contract pricing arrangement has been created to fill the gap between these two poles, the fixed-price-incentive (FPI) contract.

In the FPI contract, variations in actual costs from the originally negotiated estimate are shared by the owner and contractor. Initially a target cost, a target profit, and a sharing proportion are negotiated. The target profit is usually a certain percent of the target cost. Assume that the contractor's sharing proportion was negotiated at 20 percent and actual audited costs turn out to be $1 mil-

lion less than target cost, $200,000 is added to the contractor's target profit, the remaining $800,000 reverting to the owner. Conversely, if actual costs exceed the target cost then the contractor's profit will be reduced by 20% of the excess and the owner will absorb the balance.

Scherer,(67) Fisher,(68) and McCall(69) state that the FFP and CPFF pricing arrangements are special cases of the FPI pricing arrangement and that the entire spectrum of contractual pricing arrangements can be represented by an analytically tractable algebraic formula for the FPI arrangement. Let π_T be the negotiated target profit amount, Z the contractor's sharing proportion, C_T the negotiated target cost, and C_A the actual cost charged to the contract. Then, the contractor's profit, π_C can be expressed as follows:(66)

$$\pi_C = \pi_T + Z\ (C_T - C_A) \tag{8}$$

The fact that the FFP and CPFF contracts are special cases of the FPI pricing arrangement can be demonstrated by showing the range of Z for each contract type:

Contract Type	Sharing Proportion
FFP	$Z = 1.0$
FPI	$0 < Z < 1$
CPFF	$Z = 0$

It seems clear that contractor profit can be maximized and/or risk minimized by the proper selection of the

parameter Z for the contract pricing arrangement. Research by Scherer(70) confirms that contractors simultaneously exhibit both profit maximization and risk minimization behavior and can be expected to be motivated by both. Since the sharing proportion, Z, relates directly to both of these motivating factors, the adoption of the FPI pricing arrangement to the complete CM format can provide the vehicle through which to relate the contractor's motivating factors and the owner's utility for plant maintenance.

By adopting the FPI pricing arrangement and computing contractor profit according to equation no. (8), it is seen that the contractor can maximize his profits by minimizing C_A and maximizing Z. It is logical that the owner shall want to capitalize on this contractor motivation and therefore the owner should somehow relate Z to his measure of maintenance effectiveness or MAU. If the factor, Z, is directly related to owner MAU then as the contractor attempts to maximize Z he in turn maximizes the owner's MAU. In this context, Z is not a "constant" negotiated between the contractor and owner but rather it is a "variable" controllable by the contractor.

In order to relate Z and owner utility, Z must be expressed in terms of an owner-held measure of effectiveness. In this regard, it is appropriate to discuss how a coherent measure of effectiveness can be formulated that will

adequately reflect the owner's utility for contractor acts.

5.3 A Measure of Effectiveness

The adjustment of contractor reward according to an owner-held measure of effectiveness has had extensive application by the Pennsylvania Department of Transportation (PennDOT) in the area of contractor prequalification. PennDOT computes the dollar volume of construction that each potential contractor is qualified to perform for them according to the formula:(71)

$$Q = F \left(C + \frac{L + E}{2}\right) \qquad (9)$$

where Q = qualification amount,

C = net working capital,

F = assigned ability factor (1 to 12),

L = line-of-credit statements, and

E = book value of equipment.

Within this formula, the "assigned ability factor" or "F" factor takes on the role of a PennDOT measure of effectiveness for the contractor. To determine the F factor for each contractor, PennDOT rates each contractor for (a) attitude, (b) cooperation, (c) management capabilities, (d) work performance, (e) equipment, and (f) organization. Each of these attributes is weighted and exhibited in an MAU matrix where:(72)

S_1 = cooperation + attitude,

S_2 = equipment,

S_3 = organization + management, and

S_4 = work performance.

The utiles or "S" values are weighted and summed to compute F as follows:(72)

$$F = \frac{S_1}{6} + \frac{S_2}{6} + \frac{S_3}{6} + \frac{S_4}{2} . \qquad (10)$$

F, then, is a measure of the PennDOT multi-attribute utility for each contractor's ability.

Since this "measure of effectiveness" concept has had successful application with PennDOT, it would appear that a similar concept could be applied to the complete CM format. By setting Z equal to the factors that make-up the owner's multi-attribute utility, the contractor's effort in maximizing Z is directed toward those aspects of the contract of most importance to the owner. In this regard, it has been stated in Chapter 4 that the owner's MAU is a function of plant production, quality control, efficiency, and reliability. Thus, the proper measure of effectiveness for the owner to establish as the argument of Z is:

$$Z = f\ (\text{prod, qual, eff, rel}). \qquad (11)$$

Referring to Grey's recommendation(73) that a contractor's performance award be based on his relative effectiveness in

fulfilling performance elements (attributes) established by the owner and judged by the owner, it is clear that the owner must establish a "benchmark" for each of the attributes from which he may measure the contractor's relative effectiveness in fulfilling the owner's MAU. He must also establish a threshold performance limit below which any further deterioration in performance is unacceptable. A reasonable benchmark for each of the attributes might be the average plant performance in each attribute during the last year of operation. A reasonable threshold limit might be set at 3/4 of the benchmark. Adopting these measures as the plant ideal and then comparing the actual plant performance to the ideal, the expression for the sharing proportion would become:

$$Z = f\left(\frac{\text{actual-threshold prod}}{\text{ideal production}}, \frac{\text{actual-threshold qual}}{\text{ideal quality}}, \frac{\text{actual-threshold eff}}{\text{ideal efficiency}}, \frac{\text{actual-threshold rel}}{\text{ideal reliability}}\right) \quad (12)$$

Since the owner is indifferent in his preferences among the four attributes and Z must be limited to the range $0 \leq Z \leq 1$, the algebraic formulation of Z can be conceptualized as a weighted average of the four owner-held attributes as follows:

$$Z = \frac{(P_A - 3/4P_i)}{P_i} + \frac{(Q_A - 3/4Q_i)}{Q_i} + \frac{(E_A - 3/4E_i)}{E_i} + \frac{(R_A - 3/4R_i)}{R_i} \quad (13)$$

$$0 \leq Z \leq 1$$

Now, combining equations (13) and (8) we get:

$$\pi_C = \pi_T + \left[\frac{(P_A-3/4P_i)}{P_i} + \frac{(Q_A-3/4Q_i)}{Q_i} + \frac{(E_A-3/4E_i)}{E_i} + \frac{(R_A-3/4R_i)}{R_i}\right](C_T-C_A) \quad (14)$$

Expression (14), then, directly relates contractor profit (losses) to the effectiveness of plant performance in the four major owner-held utility attributes. It is now appropriate to discuss how this relationship can operate to engender honesty on the part of the contractor in his assessment of MAU probabilities.

5.4 Reward to Engender Honesty

In 1969, Howard Raiffa(74) developed a theory on "Natural Imputed Reward Structures" and discussed the role that such reward structures play in providing incentives for honest probability assessments. In this regard, the Raiffa theory is pertinent to the plant owner's motivating problem and is summarized below.

Suppose that the contractor, acting as an expert probability assessor, announces a probability measure $\underline{p} = (p_1, \ldots, p_n)$, where p_i is the probability of event E_i, and then acting as the owner's maintenance decision maker, he uses this distribution in the maintenance job scheduling problem. In particular, suppose that if he chose

maintenance job m_k and event E_i occurs, then the owner's utility payoff is $u_i(m_k)$. If the contractor says $\underline{p}$, then an optimal maintenance job shall be chosen to maximize:(74)

$$\Sigma_{i=1}^{n} p_i \ u_i \ (m_k). \tag{15}$$

Let the optimal maintenance job, for a given $\underline{p}$, be denotedly $m^0(\underline{p})$. Hence, if the contractor says $\underline{p}$ and then selects $m^0(\underline{p})$ and if event E_i occurs, then the owner's utility payoff is $u_i \ m^0(\underline{p})$, which can be abbreviated as $U_i(\underline{p})$.

A natural imputed reward structure for the contractor can be defined as follows: If he says $\underline{p}$ and E_i occurs, his reward is:(74)

$$a + b \ U_i \ (\underline{p}) \tag{16}$$

for some a and $b > 0$.

Suppose that a and b are chosen such that the contractor has a linear utility function for reward payoffs. In this case if he really feels $\underline{\pi}$ and says $\underline{p}$, then his expected reward is:(74)

$$\bar{r} \ (\underline{\pi}, \ \underline{p}) = a + b \ \Sigma_{i=1}^{n} \pi_i \ U_i \ (\underline{p}). \tag{17}$$

According to Raiffa,(74) if the owner uses this natural imputed reward structure, "...then there is no incentive for our expert not to tell the truth, since:

$$\bar{r} \ (\underline{\pi}, \ \underline{\pi}) \geq \bar{r} \ (\underline{\pi}, \ \underline{p}), \text{ for all } \underline{p}.$$

This follows readily since:

$$\bar{r}\ (\underline{\pi},\ \underline{p}) = a + b\ \Sigma_i\ \pi_i u_i\ m^0(\underline{p}) \leq$$

$$a + b\ \Sigma_i\ \pi_i u_i\ m^0(\underline{\pi}) = \bar{r}\ (\underline{\pi},\ \underline{\pi})."$$

The key implication of the Raiffa theory is that the reward structure pays off the contractor in accordance with the extent to which the owner's utility payoff, $u_i(m_k)$, is actualized. In this regard, the natural imputed reward structure gives the contractor a virtual share in the owner's business. In so doing, an explicit reward structure is not presented to the contractor since he cannot quantify the results of each of his acts in an explicit sense. However, Savage states:(75)

> "Business sharing does not present the expert with an explicit reward structure in any business complicated enough to provide a more than mechanical role for the managers, in particular in any business in which there are other uncertainties than those about which the expert is consulted, but an implicit structure is as effective in principle as an explicit one."

Additional writings on honest reward functions that support the Raiffa theory can be found in De Finetti,(76) Winkler,(77) and Pickhardt.(78)

It is asserted that the reward structure implied by expression no. (14) is a natural imputed reward structure. In the context of that expression, the contractor gains only if the owner gains and his maximum effort is accordingly

directed toward the area of plant maintenance of most importance to the owner. The motivating factor that provides the contractor with his incentive is profit maximization.

It was previously asserted, however, that research has shown that contractor's have a dual nature when faced with situations of uncertainty.(70) Contractors tend to exhibit both profit maximization and risk minimization behavior when faced with uncertainty. The assessment of risk is a major component in the decision criteria of businessmen.(79) In this regard, it is considered appropriate to develop a reward structure that will capitalize on the contractor's risk minimization behavior as well as his profit maximization behavior.

It is clear that the contractor will have a positive incentive to maximize Z as long as his actual costs are less than the target costs. However, if for some reason C_A should exceed C_T it will be in the contractor's interests to minimize Z and thus remand a large portion of the losses to the owner. This ambiguity would have catastrophic consequences for the owner since the tendency would not only be to minimize his MAU but the owner would also suffer a large portion of the contractor's financial losses.

In order to avoid this problem and to capitalize on the contractor's risk minimization behavior, the reward

structure must include a mechanism that allows the contractor to minimize his losses by maximizing Z. This goal can be achieved by computing contractor profit based on two different expressions, with the applicable expression depending on whether or not $C_T - C_A \geq 0$.

Suppose that $C_T - C_A \geq 0$, then the contractor's motivation would tend to be to maximize his profits and he would maximize Z in expression no. (8). On the other hand, suppose that the contractor's costs are greater than he anticipated and $C_T - C_A < 0$, then expression (8) would provide a negative motivation since he now is interested in minimizing his losses.

It is in the owner's best interests, then, to derive an expression through which the contractor can minimize his losses by maximizing Z. Such an expression is as follows:

$$\pi_C = \pi_T + (1 - Z)(C_T - C_A) \tag{18}$$

For those instances in which $C_T - C_A < 0$, the contractor can minimize his losses as long as he provides a maximum Z value.

The two expressions for the FPI pricing arrangement previously developed provide a natural imputed reward structure that covers both profit maximization and risk minimization behavior on the part of the contractor. The contrac-

tor can maximize his profits or minimize his losses only insofar as he maintains a high value of Z. In the context of the Raiffa theory, then, the contractor is obliged to provide an honest assessment of the owner's MAU probabilities for each maintenance job.

6.0 CONCLUSION

6.1 Summary

It has been the primary objective of this work to develop a priority assessment and scheduling decision model for a complete CM agreement. The significance of such a model is perceived as being its possible contribution to the resolution of the contractor decisions ambiguity that exists in current CM contracts. A contractual framework has been needed that provides a low contractor risk alternative to force account maintenance and includes controls that will protect the plant owner's interests. Accordingly, since the low contractor risk required precludes the use of firm fixed-price pricing arrangements and existing CM practices in cost-plus pricing arrangements do not adequately protect the owner's interests, a contract framework has been needed that contains a pricing arrangement between fixed-price and cost-plus but includes the necessary features to ensure that contractor decisions are in the owner's best interests. This thesis has been dedicated to the development of such a contract framework.

In the development of a complete CM scheduling decision model, it has been shown that a number of plant owners, particularly in the private sector, prefer to have a complete CM service but fall short of this goal because of

the contractor decisions versus owner interests dilemma inherent in present CM methods. A review of the experience with existing CM contracts strongly indicates that in order to protect the interests of the plant owner a basic requirement for any CM agreement must be the inclusion of the principles of maintenance management as contract specifications.

The decision-making structure of maintenance management is designed to deal with the two broad areas of maintenance action:

(a) routine preventive maintenance in which the maintenance requirements calling for decisions can be anticipated and the decisions "programmed" into the program structure; and

(b) non-repetitive corrective maintenance in which the maintenance decisions cannot be anticipated and "programmed" a priori.

The concept of programming decisions in the maintenance management system tends to protect the owner's interests since it removes opportunity for autonomous contractor decisions that may conflict with owner interests. Where decisions cannot be programmed, it has been shown that the owner's interests can be protected through maintenance management by requiring:

(a) continuous inspections to determine emerging corrective maintenance requirements;

(b) planning and estimating to quantify the work identified;

(c) determining job priority through an owner-created Multi-Attribute Utility (MAU) model; and

(d) scheduling jobs according to MAU priority within the constraints of owner-established limits on material and labor.

In order to gain maximum effectiveness from the CM maintenance management program it was asserted that a mechanism must be included in the contract to assure contractor quality control (CQC). The CQC function is designed to provide positive feedback from the contractor to the owner that the contractor is indeed performing the various functions required in the maintenance management program. Several existing contracts were reviewed that successfully incorporate CQC principles. The contracts included NASA,(80) the U.S. Navy,(81) Getty Oil,(82) and Columbia Nitrogen Corporation.(83) The essence of the CQC system is that it requires the contractor to control his own fulfillment of the contract specifications and to formally certify to the owner in writing that he has done so. Additionally, the owner inspects the results of the contractor's actions and maintains surveillance over the progress of the contractor's maintenance management program. It has been asserted that through these three elements, i.e., contractor quality control, owner in-

spection, and owner surveillance, coupled with the principle of "honest reward" the owner is assured that the contractor is physically fulfilling the contract specifications.

The maintenance management component of the proposed CM framework provides an effective means of programming "routine" CM decisions and the CQC-honest reward component insures compliance with the specifications. The remaining issue that evolves from a complete CM agreement is how to resolve corrective maintenance uncertainties a priori in such a way that the owner's interests are protected with minimal risk to the contractor. A method was proposed that uses the time-proven concept of "optimization within budgetary constraints" for work scheduling.

In order to minimize the contractor's uncertainty about corrective maintenance requirements, and, consequently, his perception of the risk involved in accepting the contract, the proposed CM framework requires explicitly that the contractor provide a maintenance management service that includes PM inspection, planning and estimating, work input control, material coordination, shop scheduling, job accomplishment, and management reporting. PM inspections and planning determine emerging corrective maintenance requirements and quantify those requirements. In the work input control element, decisions must be made whether or not to accomplish each specific job considered for work input.

The owner would desire that these decisions always select jobs for accomplishment that contribute to his measures of plant effectiveness and do so within the resources that he has available for the purpose. In this regard, since it is not possible to program the work input control decisions a priori, the proposed CM framework introduces certain "mechanisms" that would limit contractor risk but meld the contractor work input decision process to include owner-held decision criteria. Additionally, a reward structure is introduced to engender contractor honesty in the assessment of work priorities.

The work input control mechanisms proposed for the complete CM framework provide two functions: (a) contractor risk minimization, and (b) optimization of maintenance effectiveness within owner established constraints. An important aspect of contractor risk minimization is the limitation of the variance of magnitude of individual corrective maintenance jobs that the contractor will be responsible for accomplishing. This goal is achieved by establishing a mechanism that sets a job magnitude limit (say $8000 in direct materials and 1000 manhours of direct labor) and specifies that the contractor submit every job considered for work input to a preliminary "threshold evaluation" to determine if the job falls outside the envelope of acceptable magnitude. If the job falls outside the envelope, the con-

tractor is directed to submit the job to the owner for action and the contractor has no further responsibility for the job. The threshold evaluation mechanism has been used successfully by the U.S. Navy in its Contender Evaluation and Selection Technique (CONTEST)(84) for selecting R and D contractors and in its Shore Facilities Planning and Programming System(85) for managing facilities requirements.

Two additional contractual mechanisms are included to actualize a "maintenance optimization within budgetary constraints" concept. One mechanism formally defines in a behavioral decision model the criteria upon which optimization is based. The behavioral model "programs" in the contract the weighted attributes of the owner's utility for plant maintenance and is consequently called a Multi-Attribute Utility (MAU) model. The MAU model provides the basis for a contractor determination of the relative utility of each job considered for work input and requires only that the contractor assess the probability that each job is "superior to norm". In this regard, the relative priority of each maintenance job is established based on owner preferences and at the exclusion of contractor preferences. Therefore, the MAU model mechanism contributes to maintenance optimization as measured from the owner's viewpoint rather than from the contractor's viewpoint.

The next mechanism involves the establishment of a corrective maintenance "budget" in the contract and re-

quiring the contractor to select the highest priority jobs determined from the MAU model for accomplishment within the budget. The "budget" would consist of an owner established limit on manhours of direct labor and dollar value of direct materials to be allocated for corrective maintenance. Through these explicit limits introduced as bid items in the contract, the contractor has the necessary information upon which to base his proposal for the corrective maintenance aspect of the plant maintenance requirements.

In order to actualize the functional aspects of the maintenance management program and the work input control mechanisms, the proposed contract framework introduces the concept of a "natural imputed reward structure" to engender contractor incentive to perform in the owner's best interests. The reward structure relates contractor profit maximization and loss minimization behavior to the owner's measure of plant effectiveness, Z, where Z is a function of the actual versus ideal plant production, quality control, efficiency, and reliability.

A review of the overall contractual system developed in the thesis indicates that the system incorporates five basic features for owner control of contractor actions and consequent protection of owner interests. The first feature is that of programmed decisions in the maintenance management program. The contribution of this feature to

the protection of owner interests is to minimize the opportunity for autonomous contractor decisions.

The second feature is that of contractor quality control. The contribution of this feature is the assurance to the owner that the maintenance management functions specified in the contract are being carried out.

The third feature is that of programmed owner preferences for maintenance utility attributes and consequences of maintenance acts in job priority assessment. The contribution of this feature to the protection of owner interests is to inject owner preferences into the work input control process at the exclusion of contractor preferences.

The fourth feature is that of maintenance optimization within resource constraints. The contribution of this feature to the protection of owner interests is that it provides the vehicle through which the owner might gain the maximum benefit possible, in terms of maintenance, within the resources that he has made available for that purpose.

The fifth feature is that of a natural imputed reward structure to engender honesty on the part of the contractor. The contribution of this feature to the protection of the owner's interests is that it provides the medium through which the contractor may be motivated to be honest and responsible in his efforts as they apply to all areas of maintenance management.

A further review of the proposed contractual system shows an administrative framework, fully defined in a plant manual, constructed of a maintenance management system component, a contractor quality control component, a work input control component comprised of three mechanisms, i.e., threshold evaluation, MAU model, and budget, and an honest reward structure component. Embodied in these components and mechanisms are certain features that contribute to protecting the owner's interests and other features that contribute to minimizing the risk that may be perceived by the contractor. All of the components are interrelated through the measure of maintenance effectiveness, Z, as are the owner's interests and the contractor's motivational factors. An illustration of how the various aspects of the proposed contractual system interrelate is provided in Figure 6.

The positive relationship of Z to the various aspects of contractor motivation and owner interests raises a number of questions about the need for a decision theoretic approach to the contract. Indeed, if the contractor is motivated to maintain a satisfactory level of maintenance because an honest reward structure is offered to him, why should the owner want to build an MAU model to protect his interests?

There are two basic reasons why the owner should include an MAU model in his contract. The first is the con-

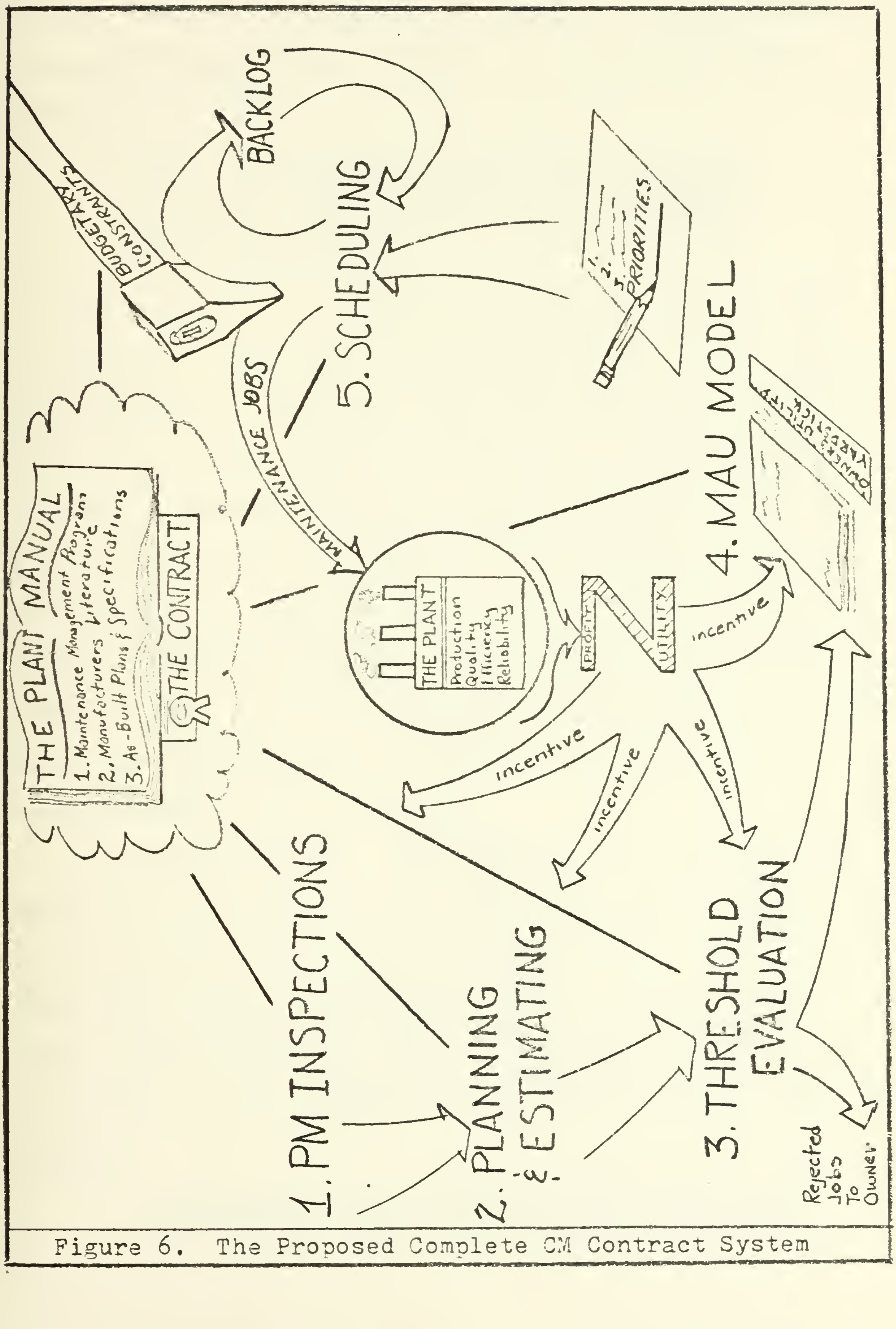


Figure 6. The Proposed Complete CM Contract System

cept of "bounded rationality" as coined by Simon(86) but originally discussed by Franklin. It is recalled that Franklin said:(46)

> "When these difficult cases occur, they are difficult, chiefly, because while we have them under consideration, all the reasons--pros and cons--are not present to the mind at the same time."

In this regard, it is prudent to provide a decision model that places "...all the reasons--pros and cons--..." before the contractor. The second important reason for including a MAU model in the contract is based on the tendency for managers to exhibit variance in their decision making behavior as discussed by Bowman.(47) In order to minimize this variance, a decision model that disciplines the decision process is necessary. Although honest reward might correlate contractor motivation and owner utility, it could not control the realities of bounded rationality and decision variance in the contractor.

Another question that arises is "if all of the expenses of the contract can be identified and quantified by the contractor, then wouldn't the contractor's expected actual costs, $E(C_A)$, approximately equal the negotiated or bid cost (C_T) and therefore negate the incentive factor in $\pi_C = \pi_T + Z(C_T - C_A)$?" Research by McCall(87) indicates the following:

> "...Because of the peculiar sharing rule that characterizes these contracts (FPI contracts),

> it is difficult for the government to distinguish between high and low-cost firms on the basis of the submitted bids or target costs. The fact that efficient or low-cost firms must share some of their profits-difference between target costs and actual costs-with the government induces them to submit cost estimates higher than expected costs."

It is logical to assert that a potential contractor can gain by increasing the target costs to a level higher than his expected actual costs and therefore his profit maximization motivation will cause him to do so. Assuming, however, that competitive negotiations determine the successful contractor; the fact that the owner has most of the information necessary to prepare a viable estimate of costs and establish a sound negotiating position coupled with the element of competition present in the transactions, will tend to minimize the magnitude of difference between $E(C_A)$ and C_T. A few areas where a potential contractor might negotiate for a higher target cost than he expects his actual costs to be are direct labor rates, home office overhead, field overhead, material indirects, and labor indirects. Based on documented experience with past FPI contracts, then, and the nature of the proposed FPI formula, it is asserted that C_T will tend to be greater than $E(C_A)$ and a positive incentive to maximize Z is therefore provided.

A third question that can be raised when one assesses the implications of the risk minimization concepts proposed in the complete CM system is "does the contractor

assume any risk at all for plant malfunctions?" The answer to this question lies in whether $C_T \neq C_A$. Due to the honest reward structure, any plant failures would tend to reduce Z and as long as $C_T \neq C_A$ the contractor's profits would decrease or his losses would increase by an amount proportional to the reduction suffered in Z. In this regard, the contractor does assume risk for plant malfunctions. Based on the tendency of contractors to negotiate (or bid) a value of C_T greater than $E(C_A)$, it is asserted that the direct correlation of Z to plant performance induces a positive incentive on the part of the contractor to avoid plant malfunctions.

The questions raised above about the proposed decision theoretic approach to contractual maintenance attempt to disassemble the basic assumptions upon which the contract framework is based. In this regard, the interrogation of the system foundations is an important part of the decision theoretic, operations research, systems analysis, or any other quantitative approach to problem solving. Only the most unsophisticated systems can be abstracted to mathematical formulae and therefore must involve human judgement. To the extent that systems do involve human judgement, these judgements must be subject to open and explicit analysis. It is considered appropriate to quote the views of Dr. Alain Enthoven, Assistant Secretary of Defense (Systems

Analysis), concerning the role of human judgement and open analysis in systems analysis:(88)

> "The essence of systems analysis is not mysterious, nor particularly complicated, nor entirely new, nor of special value only to Defense planning. Rather, it is a reasoned approach to highly complicated problems of choice characterized by much uncertainty; it provides room for very differing values and judgements; and it seeks alternative ways of doing the job. It is neither a panacea nor a Pandora's box.
>
> "Decisions must be made by responsible officials on the basis of fact and judgment. Systems analysis is an effort to define the issues and alternatives clearly, and to provide responsible officials with a full, accurate, and meaningful summary of as many as possible of the relevant facts so that they can exercise well-informed judgment; it is not a substitute for judgment.
>
> "It helps by isolating those areas where judgment must be applied and by indicating to the decision maker the potential significance of each of the alternatives he might choose. Systems analysis is not a wholly rational basis for decision making or a technocratic utopia where judgment is a machine product.
>
> "Far from it. It is based on the fact that most decisions in Defense are at least partly susceptible to rational treatment, and it tries to deal with these in a disciplined way, leaving the responsible decision makers more time to ponder the imponderables and weigh the intangibles.
>
> "...Systems analysis is a method of interrogation and debate suited to complex, quantitative issues. Systems analysis is a set of ground rules for constructive debate; it gives the participants useful guidelines for proceeding to clarify and resolve disagreements. It requires the participants to make their methods of calculation and

> their assumptions explicit so that they can be doublechecked; it helps to identify uncertainties, makes these uncertainties explicit, and aids in evaluating their importance; and it identifies and isolates issues.
>
> "Systems analysis usually includes some calculations. Where appropriate, it includes the application of modern methods of quantitative analysis, including economic theory, mathematical statistics, mathematical operations research, and various techniques known as decision theory. However, systems analysis is not synonymous with the application of these mathematical techniques, and much of the most important systems analysis work in the Department of Defense does not use them.
>
> "Decisions of the kind we are discussing turn in large part on judgments about questions of value and uncertain or unknowable facts. Nobody claims that systems analysis automatically produces good decisions or that all the decisions aided by systems analysis have been good ones. I am merely suggesting that systems analysis has proven to be a useful tool which can help the decision maker.
>
> "The potential of systems analysis is great in clarifying debate over program issues, in stimulating and recognizing new solutions to problems, and in helping the Government to spend money wisely. Within the limits of what any improvement in management can do, I believe that systems analysis has the potential to be a most important innovation in government management."

Within the limits of what any improvement in management can do, then, it is asserted that the multi-attribute utility model developed herein achieves the objective stated for this thesis. Accordingly, it is appropriate to discuss the steps necessary to implement such a model.

6.2 Implementation

The major steps for the plant owner to take in implementing the contractual framework proposed in this work include the following:

(a) ensure that the plant manual and the maintenance management program contained therein suitably describe the desired maintenance policy and program;

(b) ensure that manufacturer's literature is available on-site on all major plant components;

(c) ensure that the plant as-built drawings are available on-site;

(d) determine the equal-weight attributes that comprise the owner's utility for plant maintenance and create a multi-attribute utility decision model;

(e) determine the threshold limit for individual job magnitude beyond which the contractor will not be responsible for accomplishment;

(f) based on prior years' operating records and the owner's personal experience, determine the magnitude of direct labor and direct material to establish as the corrective maintenance "budget";

(g) based on the owner's preferences for plant performance and prior years' operating records, establish the ideal or "benchmark" and threshold levels of production, quality control, efficiency, and reliability and formulate

a measure of effectiveness, Z;

(h) formalize a contractor quality control procedure, including report forms and administration format, and enter it into the Plant Manual;

(i) merge the various factors thus created into a comprehensive contract specification; and

(j) after requesting proposals from interested contractors, competitively negotiate the contract.

Beginning with a discussion of the owner's maintenance management program contained in a plant manual, a review of Appendix A gives an indication of the magnitude of effort required to develop these components for the owner's plant if they do not already exist. Because of the magnitude of effort required to develop a viable maintenance management program for a process plant, it has been a necessary assumption of this thesis that such a program is in existence for performance by the owner's in-plant forces before serious consideration is given to developing a complete CM contract. This assumption is not considered restrictive since research indicates that many grass-roots* plant owners have maintenance management programs developed for their plants during or soon after plant construction.

The implementation of the maintenance management program in a complete CM contract can be accomplished by

---

*Grass-roots plants are those plants that are under construction or have been recently completed.

stating in the contract detail specifications that maintenance will be in accordance with the procedures outlined in the Plant Manual.

A necessary adjunct to the planning and estimating (P and E) element of the maintenance management program is a complete set of manufacturers literature and as-built drawings. Although these items are often misplaced or inadvertently destroyed in "seasoned" process plants over the years, their importance to the protection of the owner's interests cannot be overstressed. Therefore, an assumption of this thesis in developing a contractual framework for complete CM has been that complete sets of manufacturer's literature and as-built plans exist.

In many cases, if complete sets of the literature and plans do not exist, experience has shown that literature can be acquired from equipment manufacturers for a small fee. Similarly, many architect-engineer firms maintain microfilm files on past projects and will make copies of desired plans for a nominal fee. Accordingly, when complete sets of the literature and plans are established, they can be made a part of the contract by stating in the P and E element of the maintenance management program that all replacement materials, assemblies, and procedures will be in accordance with those recommended in the manufacturer's literature. Similarly, it should be stated that all repairs

and replacements of plant components will be in accordance with the existing as-built design plans and specifications.

The next step in implementing the proposed complete CM framework is to construct the three work input control mechanisms, i.e., MAU model, threshold evaluation, and budget. First, the MAU model is constructed in a method as explained in Chapter 4. The owner (or his designated consultant) must determine the equal weight attributes that comprise the owner's utility for plant maintenance. In most cases these attributes will be production, quality control, efficiency, and reliability. Then, within each of these general factors, the owner must determine the several equal weight elements that provide a thorough yet realistic definition of the owner's utility structure within each factor. The number of elements under each factor must equal the number of elements under any other factor. Within each factor, if each element is equal in weight to the other elements in that factor, and if all of the factors are of equal weight, then by the principle of transitivity, any element in any factor should be equal in weight to any other element regardless of the factor. Listing the factors and elements in matrix form, then, and introducing probability assessment procedures whereby the probability of "superior to norm" is assessed for each alternative job for each factor/element, the owner's expected utility for each maintenance job can be

provided.

The implementation of the MAU matrix in the proposed complete CM contract can be accomplished by introducing the MAU model into the work input control element of the maintenance management program. As a standard procedure in the work input control element, the owner can require that all jobs to be considered for work input will be analyzed through the MAU model and each job's relative priority will be established based on the magnitude of utility assessed from the model.

Prior to being considered for work input, each job must pass a threshold evaluation to determine if that job falls outside the envelope of acceptable magnitude. In order to implement the threshold evaluation mechanism, the owner must first determine the magnitude of the limits on direct labor and direct material that he wishes to establish the job threshold. Based on experience with the U.S. Navy's Shore Facilities Planning and Programming System an acceptable job magnitude for in-plant responsibility is $25,000 total project cost or approximately 1000 manhours of direct labor and $8000 in direct materials.

The threshold evaluation mechanism can be implemented in the contract by introducing the labor and material limits in the work input control element of the maintenance management program. The owner should then introduce

procedures requiring that each job to be considered for work input first be evaluated to determine if it falls outside the envelope of acceptable magnitude. The procedures should require that those jobs which fall outside the envelope of acceptable magnitude be remanded to the plant owner for a determination of subsequent action.

The third work input control mechanism that the owner must establish is the artificial annual "budget" for direct labor and materials to be used in corrective maintenance. In the first year of the contract, the magnitude of direct labor and materials should be based on the owner's desire to reduce the backlog of work from the previous year and his "expectation" of maintenance requirements to be determined during the contract year. The final limits selected by the owner will be an indication of the level of maintenance that he desires for the plant. Some plant owners follow "rules of thumb" in determining the appropriate level for plant backlog(89) and correction of anticipated deficiencies.(90) From these "rules of thumb", which in most cases are based on plant replacement value and type construction, the plant owners that use them are able to subjectively establish each year's maintenance budget.

Once the labor and material limits are established by the owner, the budget mechanism can be implemented in the contract in two steps:

(a) submit a contract bid item calling for an explicit number of manhours of direct labor and another bid item calling for an explicit dollar value of direct materials to be used for corrective maintenance; and

(b) introduce procedures in the work input control element of the maintenance management program that call for the selection for accomplishment each month, within the labor and material limits, those jobs with the highest MAU.

After the work input control mechanisms are established the owner must determine his desired measure of maintenance effectiveness, Z. The parameter Z must embody two primary features:

(a) it must measure the actual plant performance versus the owner's ideal; and

(b) it must approach zero as plant performance decays toward an owner-established threshold of unacceptability.

An expression that embodies these two features as they apply to a process plant is:

$$Z = \frac{(P_A - 3/4P_i)}{P_i} + \frac{(Q_A - 3/4Q_i)}{Q_i} + \frac{(E_A - 3/4E_i)}{E_i} + \frac{(R_A - 3/4R_i)}{R_i}$$

$$0 \leq Z \leq 0$$

In order to create an expression for Z, the owner should use the factors that make-up his MAU structure. He should then decide the quantitative level for each factor

that he considers realistically attainable within the resources that he is making available for the contract and establish these factor levels as the "ideal". He must then determine a performance level for each factor below which performance is unacceptable. This performance level is the threshold of unacceptability. The above expression is only one of many that can be used to abstract the owner's measure of maintenance effectiveness in this regard.

When the expression for Z has been determined, it can be implemented in the contract by specifying that contractor compensation will be based on monthly payments of actual invoiced cost (C_A) plus a contractor profit computed based on the formulae:

$$\pi_C = \pi_T + Z\ (C_T - C_A);\ C_T \geq C_A$$

or,

$$\pi_C = \pi_T + (1 - Z)(C_T - C_A);\ C_T < C_A.$$

Some maintenance contractors consider the practice of invoicing actual costs an advantage worthy of espousal. In defense of CM one maintenance contractor, Mr. J.A. Sullivan of Catalytic, Inc., states the following:$^{(91)}$

> "....Some of the advantages of contract maintenance are noted below: 1. The total cost of the contractor's maintenance organization is invoiced, weekly or bi-weekly, providing management with a current accurate total cost record. In addition, justification for certain expenditures can be demanded in the present tense as a matter of routine...."

In order to ensure that invoiced items are in-place and that the maintenance management program will proceed as anticipated, the owner must establish procedures for contractor quality control. As delineated in Chapter 3, CQC consists of the contractor's quality control program, owner inspection of the results, and owner surveillance of contractor administration of the maintenance management program.

The owner can implement the requirement for the contractor to establish a quality control plan by introducing a specification that requires the contractor to submit to the owner, prior to initiating the contract, an organization chart outlining the responsibilities of each position in the maintenance management program, the qualifications of each contractor employee filling the positions, and acknowledgement that the procedures and goals of the maintenance management program have been reviewed and understood. Additionally, the owner should require weekly statements from the contractor, each certified by a person designated as an officer of the company, that each of the PM inspections and procedures called for in the maintenance management program for that period were performed as specified by the contract and that all specific jobs completed were in accordance with the applicable plans and specifications.

Owner inspection is implemented by an owner review and approval of contractor management reports, spot checks on the PM inspection program, and spot checks on specific jobs in progress including the performance of material tests and monitoring as-built plans.

Owner surveillance is initially implemented by an owner review of the contractor's CQC submittal, i.e., his organization chart, etc. Continued owner surveillance is carried out by monitoring contractor management, labor turnover, trends in plant performance, and trends in actual costs.

At this point the plant owner will have established the following major components necessary for the proposed CM framework:

(a) a comprehensive maintenance management program contained in a plant manual;

(b) a complete set of manufacturer's literature;

(c) a complete set of as-built plans and specifications;

(d) a MAU model;

(e) a threshold evaluation envelope;

(f) a corrective maintenance budget;

(g) a measure of maintenance effectiveness, Z; and

(h) a CQC program.

The remaining step necessary to implement these components in a complete CM contract is to meld them together into a comprehensive whole. This is accomplished by establishing each component as an element in the maintenance management program and entering each component's respective procedural guidelines in the plant manual and the contract detail specifications, where appropriate. When properly implemented in the plant manual, the total program logic appears as shown in Figure 6. The physical "mechanics" of the program is described in the maintenance management program and work input control mechanisms. The program functions are actualized and controlled through the motivating forces inherent in the CQC element and the honest reward element.

When the owner has established a satisfactory complete CM contract document, he is then ready to request proposals from contractors interested in doing the work. Since the contract framework and incentive payment features are relatively complicated, it is considered prudent to award the contract through competitive negotiations so that any misconceptions can be cleared up during negotiations.

In this regard, it is appropriate to discuss contractor compensation and the proposed FPI contract pricing arrangement, $\pi_C = \pi_T + Z(C_T - C_A)$. The owner's prior expected value for contractor profit $E(\pi_C)$ is intimately re-

lated to his prior expected value for actual contractor costs and the expected value of Z. It is asserted that the target cost, C_T, negotiated by the owner is dependent upon his prior "expectation" of the actual costs, and further, that the target profit, π_T, should be some percentage of final negotiated target cost.(92) Thus C_T and, accordingly, π_T are dependent upon $E(C_A)$.

Now since the owner has the necessary requirements information upon which to base a viable estimate of the contractor's expected actual direct costs, his maximum allowable target cost should exceed $E(C_A)$ only by a fractional amount that he feels is necessary to provide the incentives desired in the contractor. It is stressed, however, that the owner should reward the contractor for his ability to maintain a high Z factor and therefore the owner should allow some difference between the negotiated target cost and his expectation of the actual costs.

In order to gain insight into how much the target profit should be and how much the difference between C_T and $E(C_A)$ should be, it is considered appropriate to use U.S. government FPI contracting experience as a guideline. Scherer(92) states:

> "It is customary for the government to award a higher negotiated target profit π_T to contractors who bear a relatively high financial risk--that is, who accept relatively high values of Z--than to those who bear a smaller risk. Although other factors also affect the

> value of π_T negotiated, when they are held constant π_T tends to be a monotonically increasing function of the sharing proportion, Z, chosen. For simplicity we shall assume π_T to be a quadratic function of Z:
>
> $$(5) \qquad \pi_T = \pi_T(Z) = k + hZ + mZ^2.$$
>
> Empirical evidence suggests that on the average, k is equal to roughly 6 (that is, the fixed fee on a CPFF contract, Z = 0, averages 6 percent of target cost). π_T tends to reach a maximum of about 12 with FFP contracts (Z = 1.0)."

So it would seem that a reasonable maximum for the target profit should be 6 percent of the target cost and a reasonable maximum for total expected profit, $E(\pi_C)$, would be between the 6 percent and 12 percent. The actual value should depend on how much "risk" the owner feels that he is placing on the contractor through a tight "budget" and/or a restrictive expression for Z.

Assume that the reasonable expected value for contractor profit was 9 percent. Then the owner should first determine his estimate of expected actual costs, $E(C_A)$ and negotiate a maximum value of C_T equal to 103 percent of $E(C_A)$. During negotiations, if the contractor is able to convince the owner that certain costs not considered by the owner are indeed valid costs then the owner should revise his expectation of C_A and, accordingly, C_T.

When a final value for C_T has been negotiated, the owner should negotiate a value for π_T not to exceed 6 per-

cent of C_T. Then, during the contract period if the contractor maintains a value of Z equal to 1.0 his prior expected profit should be approximately 9 percent.

With these concepts in mind it is apparent that the owner is placed in an advantageous position at the negotiating table. He has much of the same information necessary to prepare a cost estimate that the contractor has and therefore the $E(C_A)$ should tend to be equal for both parties. Since the parties are negotiating C_T, the contractor desires to maximize the negotiated value for C_T because of his profit maximization motive and the owner desires that C_T exceed $E(C_A)$ by, say, 3 percent because of contractor incentive motives. The owner, then, should be able to negotiate downward to 103% of $E(C_A)$, or a revised value of $E(C_A)$, from the initial contractor proposal for C_T.

In conclusion, the implementation of a complete CM contract framework has been proposed that provides contractor risk minimization features, features that protect the owner's interests, and features that strengthen the owner's negotiating position. It is asserted that through the adoption of such a contract framework in future complete CM contracts, the ambiguity that currently exists between contractor decisions and owner interests in CM can be alleviated and the owner can enter complete CM agreements with renewed confidence.

APPENDIX A(93)

DESCRIPTION OF THE PLANNED MAINTENANCE MANAGEMENT SYSTEM

The objective of the Planned Maintenance Management System (PMMS) is to reduce the preventive maintenance of a large number of equipment items, many of which are complex, to a set of explicit, simple tasks which can be easily scheduled, managed, performed and recorded. The system:

1. Reduces the maintenance of complex equipment to simple procedures which are easily identified and managed.
2. Defines the minimum requirements of planned maintenance.
3. Schedules and controls the performance of work tasks, inspections and tests.
4. Describes the methods, materials, tools and personnel required.
5. Provides for the prevention or detection of impending malfunctions.
6. Provides a permanent record of equipment characteristics and a maintenance history.
7. Provides periodic maintenance summary reports to plant management.

Although the PMMS is aimed at ensuring the systematic, timely, safe and complete accomplishment of equipment care and inspection, two factors must be emphasized.

1. PMMS is a tool of management rather than a substitute for a manager.
2. No system can substitute for the actual technical ability required of personnel who direct and perform the upkeep of equipment.

It is important to appreciate the scope of the PMMS. For it to be effective in achieving the highest continuous level of plant performance, all of the plant equipment must be included in the PMMS. It is not sufficient to merely attend to the mechanical and hydraulic equipment; the PMMS must pay equal attention to electrical equipment, electrical controls, electrical supply substations, measuring devices, meters and recorders, alarm sensors and alarm indicators.

The detailed description of the PMMS is contained in the remainder of this Section. First, the five basic parts of the PMMS are described, and then a number of special considerations (for municipal wastewater treatment plants) are discussed.

BASIC PARTS OF THE PMMS

The five basic parts of the PMMS are:

1. The Equipment Configuration List
2. The Maintenance Procedures
3. The Preventive Maintenance Cycle Schedule
4. The Recordkeeping System
5. The Maintenance Data Feedback System.

The Equipment Configuration List

The initial step in the development of the PMMS is the one-time accomplishment of a complete inventory of plant mechanical and electrical equipment, including a take-off of nameplate data utilizing Form M1, shown in Figures 1 and 2 on pages 22 and 23. The resultant inventory list is then restructured into the Equipment Configuration List by sorting into appropriate groupings, equipment related to each of the various plant unit process functions. Within each grouping, equipment is oriented by a numbering system described below. Table 2 is a sample page from the Equipment Configuration List of the Lower Potomac Plant.

Each item of equipment in the plant is assigned a unique five-digit identification (ID) number. The first three digits identify the function of the equipment. Table 1 is the functional numbering system for the 18-mgd Lower Potomac Wastewater Treatment Plant of Fairfax County, Virginia. The first digit identifies one of the major systems in the plant, the second identifies the subsystem and the third identifies the particular function. For example, referring to Table 1, 522 refers to all sludge pumping equipment in the sludge thickening area. The digit 5 refers to Sludge and Scum Processing; the second digit, 2, refers to Sludge Thickening; and the third digit, 2, refers to Pumping. This functional numbering system was designed to be expandable both vertically, for more complex plants with more systems, subsystems and functions, such as AWT; and horizontally, for larger plants with more parallel items of equipment, or for plant expansion.

The fourth and fifth digits of the ID number specify exactly and uniquely each item of equipment, as illustrated in Table 2. The fourth digit identifies the piece of equipment within the functional unit—the drive, for example, in a pump-motor-drive-controller unit; and the fifth digit identifies which

Table 1. FUNCTIONAL NUMBER SYSTEM

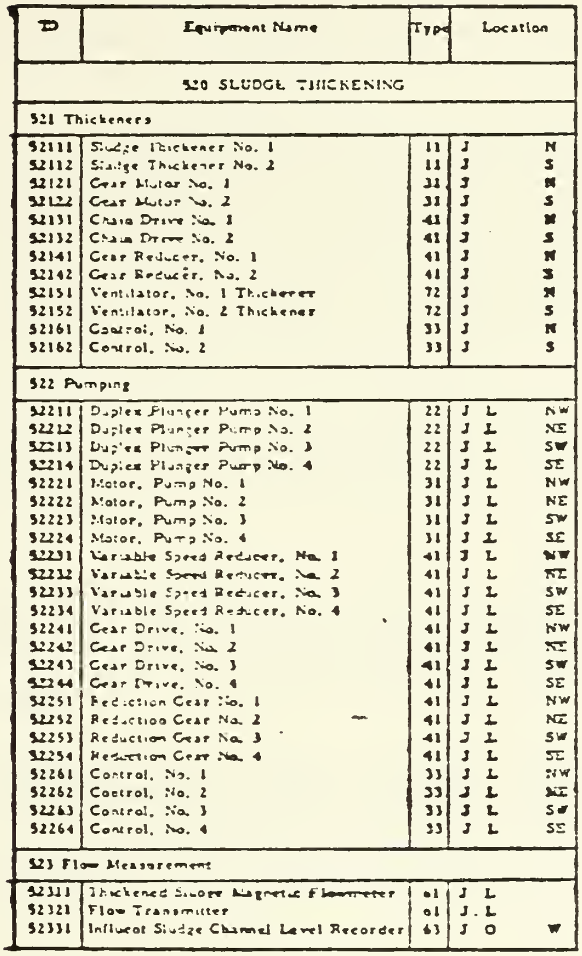
- 100 Raw Wastewater Station
  - 110 Screening
    - 111 Bar Screens
    - 112 Conveyors
  - 120 Grinding
    - 121 Grinders
  - 130 Wastewater Flow
    - 131 Pumping
    - 132 Valves and Gates
    - 133 Wet Well Level Control
    - 134 Flow Measurement
    - 135 Pump Seal Water
    - 136 Compressed Air
  - 140 Auxiliary Services
    - 141 Sump Pumping
    - 142 Ventilation
    - 143 Hoists
    - 144 Electrical Supply

- 200 Primary Treatment
  - 210 Primary Settling
    - 211 Tanks and Gates
    - 212 Sludge Collectors
    - 213 Scum Launders
  - 220 Sludge Handling
    - 221 Pumping
    - 222 Pump Seal Water
    - 223 Flow Measurement
    - 224 Sludge Degritting
  - 230 Scum Handling
    - 231 Pumping
    - 232 Pump Seal Water
    - 233 Scum Well Level Control
  - 240 Auxiliary Services
    - 241 Sump Pumping
    - 242 Ventilation
    - 243 Hoists
    - 244 Electrical Supply

- 300 Secondary Treatment
  - 310 Aeration
    - 311 Tanks and Gates
    - 312 Adjustable Weirs
    - 313 Tank Air Diffusers
    - 314 Incremental Feed Channel Air Diffusers
    - 316 Tank and Feed Channel Water Sprays
    - 316 Mixed Liquor Flow Measurement
    - 317 Diffuser Sock Washing
  - 320 Air Delivery
    - 321 Filters
    - 322 Blowers
    - 323 Flow Measurement
    - 324 Pressure Relief
    - 325 Channel Sparger Air Delivery
    - 326 Compressed Air
  - 330 Secondary Clarifiers
    - 331 Mixed Liquor Channel Air Spargers
    - 332 Mixed Liquor Channel Water Sprays
    - 333 Clarifier Mechanism and Gates
  - 340 Chemical Treatment
    - 341 Flocculant Mixing
    - 342 Flocculant Pumping
  - 350 Return Sludge
    - 351 Pumping
    - 352 Pump Seal Water
    - 353 Return Sludge Wet Well Level
    - 354 Dewatering
    - 355 Flow Measurement
  - 360 Excess Sludge
    - 361 Pumping
    - 362 Pump Seal Water
    - 363 Flow Measurement
    - 364 Dilution
  - 370 Scum
    - 371 Scum Well Level Control
    - 372 Scum Pumping
  - 380 Auxiliary Services
    - 381 Sump Pumping
    - 382 Ventilation
    - 383 Hoists
    - 384 Electrical Supply

- 400 Chlorination and Effluent Flow
  - 410 Chlorination
    - 411 Chlorine Handling and Weighing
    - 412 Evaporation
    - 413 Chlorinators
    - 414 Chlorine Detection and Venting
    - 415 Injectors and Diffusers
    - 416 Contact Chambers
  - 420 Residual Chlorine Analysis
    - 421 Analyzers
    - 422 Influent Sampling
    - 423 Effluent Sampling
  - 430 Effluent Water
    - 431 Weirs and Gates
    - 432 Level Measurement
    - 433 Return Water Pumping, High Lift
    - 434 Return Water Pumping, Low Lift
    - 435 Pump Seal Water
  - 440 Auxiliary Services
    - 441 Sump Pumping
    - 442 Ventilation
    - 443 Hoists
    - 444 Electrical Supply

Table 2. SAMPLES FROM EQUIPMENT CONFIGURATION LIST



ID	Equipment Name	Type	Location		
520 SLUDGE THICKENING					
521 Thickeners					
52111	Sludge Thickener No. 1	11	J		N
52112	Sludge Thickener No. 2	11	J		S
52121	Gear Motor No. 1	31	J		N
52122	Gear Motor No. 2	31	J		S
52131	Chain Drive No. 1	41	J		N
52132	Chain Drive No. 2	41	J		S
52141	Gear Reducer, No. 1	41	J		N
52142	Gear Reducer, No. 2	41	J		S
52151	Ventilator, No. 1 Thickener	72	J		N
52152	Ventilator, No. 2 Thickener	72	J		S
52161	Control, No. 1	33	J		N
52162	Control, No. 2	33	J		S
522 Pumping					
52211	Duplex Plunger Pump No. 1	22	J	L	NW
52212	Duplex Plunger Pump No. 2	22	J	L	NE
52213	Duplex Plunger Pump No. 3	22	J	L	SW
52214	Duplex Plunger Pump No. 4	22	J	L	SE
52221	Motor, Pump No. 1	31	J	L	NW
52222	Motor, Pump No. 2	31	J	L	NE
52223	Motor, Pump No. 3	31	J	L	SW
52224	Motor, Pump No. 4	31	J	L	SE
52231	Variable Speed Reducer, No. 1	41	J	L	NW
52232	Variable Speed Reducer, No. 2	41	J	L	NE
52233	Variable Speed Reducer, No. 3	41	J	L	SW
52234	Variable Speed Reducer, No. 4	41	J	L	SE
52241	Gear Drive, No. 1	41	J	L	NW
52242	Gear Drive, No. 2	41	J	L	NE
52243	Gear Drive, No. 3	41	J	L	SW
52244	Gear Drive, No. 4	41	J	L	SE
52251	Reduction Gear No. 1	41	J	L	NW
52252	Reduction Gear No. 2	41	J	L	NE
52253	Reduction Gear No. 3	41	J	L	SW
52254	Reduction Gear No. 4	41	J	L	SE
52261	Control, No. 1	33	J	L	NW
52262	Control, No. 2	33	J	L	NE
52263	Control, No. 3	33	J	L	SW
52264	Control, No. 4	33	J	L	SE
523 Flow Measurement					
52311	Thickened Sludge Magnetic Flowmeter	61	J	L	
52321	Flow Transmitter	61	J	L	
52331	Influent Sludge Channel Level Recorder	63	J	O	W

Location areas (refer to pages 5 and 6):

J - sludge thickening
L - plant shop and service building
O - outside

of the parallel units is being specified. The numbering system permits all similar parallel units to be grouped by the first four digits, and it permits all equipment which operates together as a unit to be grouped by the first, second, third and fifth digits.

The Equipment Configuration List, based upon this numbering system, identifies all of the equipment in the plant. In addition to the identification number and the common name, other information is provided. An equipment type number tells what the equipment item is; for example, 33 means electric controls, regardless of the function of the item in the plant (Table A-1 of Appendix III is the list of equipment type numbers for the Lower Potomac Plant). The location tells the area in the plant, the level within the area (upper, middle, lower), the location within the area (N.W., S.E., etc.) and the relative location with respect to similar or parallel items.

The Equipment Data List (illustrated by Table 3) augments the main Equipment Configuration List and is grouped by equipment type. For each item of equipment, identified by its five-digit ID number, the Equipment Data List contains the manufacturer's name, the part or model number and the serial number.

The Equipment Data List, with the equipment type number, is useful for grouping equipment with similar maintenance requirements and with similar spare parts requirements. This list is extremely useful in searching for replacement units or parts in the event of a breakdown leading to an emergency situation.

Even more detailed data are tabulated in a similar fashion to augment the Equipment Configuration List. Table 4, a sample list from the Lower Potomac Plant, shows how pumps are separately listed with their head, capacity, size, impeller and RPM; and how electric motors are separately listed with their horsepower, frame, RPM, voltage, amperage and number of phases.

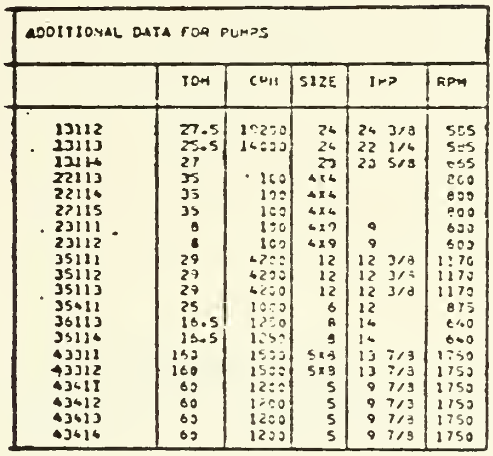
In addition to these tabular equipment inventory lists, which should be kept at a central location, the pertinent data for each item of equipment is also recorded on a single sheet of paper, Form M1, for easy reference (close to the equipment).

Form M1, "Equipment Reference Data," is an 8-1/2 x 11-inch permanent record for each item of equipment. Figures 1 and 2 show both sides of Form M1. All descriptive data from manufacturer's catalogs, drawings, bulletins and reference documents are transcribed onto Form M1. This form has three special blocks for data should the item of equipment be an electric motor, a pump or a drive or reducer. For items of equipment

Table 3. SAMPLES FROM EQUIPMENT DATA LIST

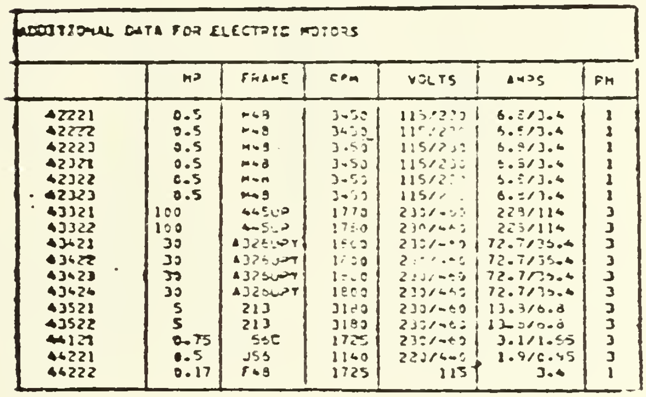
ID	Manufacturer	Part Number	Serial Number
21 Centrifugal Pumps			
13112	Fairbanks Morse	5710	K2N1044068
13113	Fairbanks Morse	5710	K2N1044069
13114	Fairbanks Morse	5710	K2N1044070
22113	Wemco Torque Flow	Model G	6895610-3
22114	Wemco Torque Flow	Model G	6895610-2
22115	Wemco Torque Flow	Model G	6895610-1
23111	Wemco Torque Flow	Model E	6895610-4
23112	Wemco Torque Flow	Model E	6895610-5
35111	Fairbanks Morse	Model 5720	K2N1044071
35112	Fairbanks Morse	Model 5720	K2N1044071-1
35113	Fairbanks Morse	Model 5720	K2N1044071-2
35411	Fairbanks Morse	5423B-28	K2N1044073
36113	Fairbanks Morse	5424D	K2N1044072
36114	Fairbanks Morse	5424D	K2N1044072-1
42211	Eastern	U-34-C, 107-3	CJ5-0802
42212	Eastern	U-34-C, 107-3	CJ5-0801
42213	Eastern	U-34-C, 107-3	CJ9-1305
42311	Eastern	U-34-C, 107-3	CJ5-0797
42312	Eastern	U-34-C, 107-3	CJ8-0800
42313	Eastern	U-34-C, 107-3	CJ5-0798
43311	Fairbanks Morse	5414E	K2N1044075-1
31 Motors, Motor and Drive Assemblies			
32621	Westinghouse	TBDP	680B101C27-6807
32622	Westinghouse	TBDP	680B101C27-6807
33321	Sterling	FBNF-1	8A2528-2
33322	Sterling	FBNF-1	8A2528-1
34221	Fairbanks Morse	KZK, T1004-2	F291030
34241	Westinghouse	M	311P178-A
35121	US Varidrive	VEU	J1421251
35122	US Varidrive	VEU	J1421249
35123	US Varidrive	VEU	J1421250
35131	US Electrical	ERHB	B121781
35132	US Electrical	ERHB	B121781
35133	US Electrical	ERHB	B121781
35421	Fairbanks Morse	KZK, T1007-2	F-457875
36123	US Varidrive	VLDHVGS	P4177843
36124	US Varidrive	VLDHVGS	P4177842
36133	US Electrical	ERHP	121781
36134	US Electrical	ERHP	121781

Table 4. SAMPLES FROM LIST OF ADDITIONAL EQUIPMENT DATA



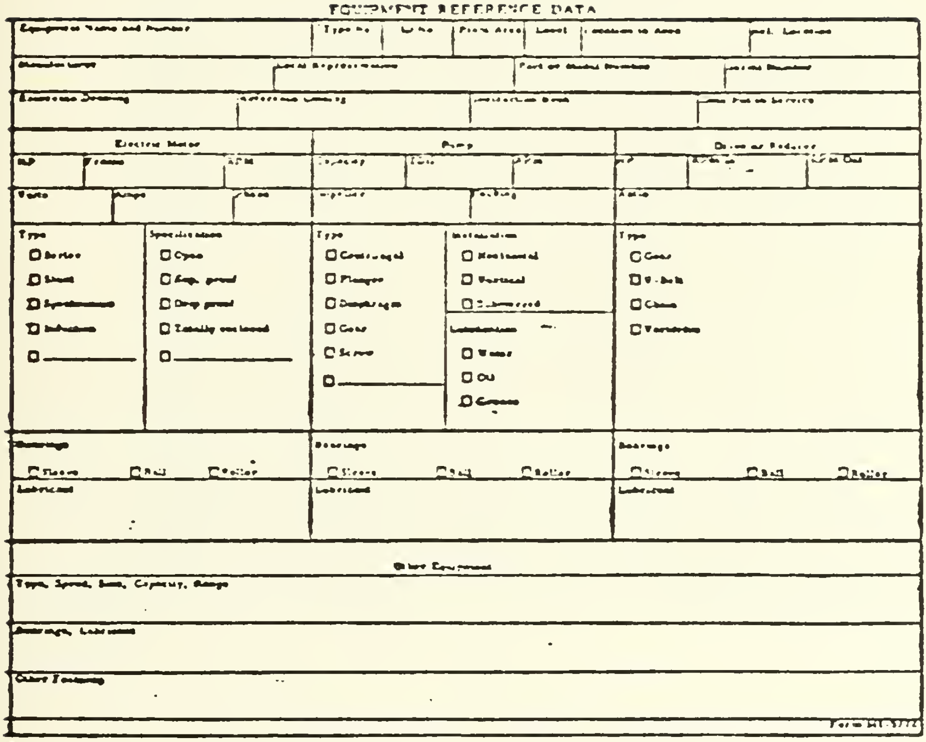
ADDITIONAL DATA FOR PUMPS

	TDH	GPM	SIZE	IMP	RPM
13112	27.5	10250	24	24 3/8	585
13113	25.5	14000	24	22 1/4	585
13114	27		20	23 5/8	865
22113	35	100	4x4		800
22114	35	100	4x4		800
22115	35	100	4x4		800
23111	8	100	4x9	9	600
23112	8	100	4x9	9	600
35111	29	4200	12	12 3/8	1170
35112	29	4200	12	12 3/8	1170
35113	29	4200	12	12 3/8	1170
35411	25	1000	6	12	875
36113	16.5	1250	8	14	640
36114	16.5	1250	8	14	640
43311	160	1500	5x8	13 7/8	1750
43312	160	1500	5x8	13 7/8	1750
43411	60	1200	5	9 7/8	1750
43412	60	1200	5	9 7/8	1750
43413	60	1200	5	9 7/8	1750
43414	60	1200	5	9 7/8	1750



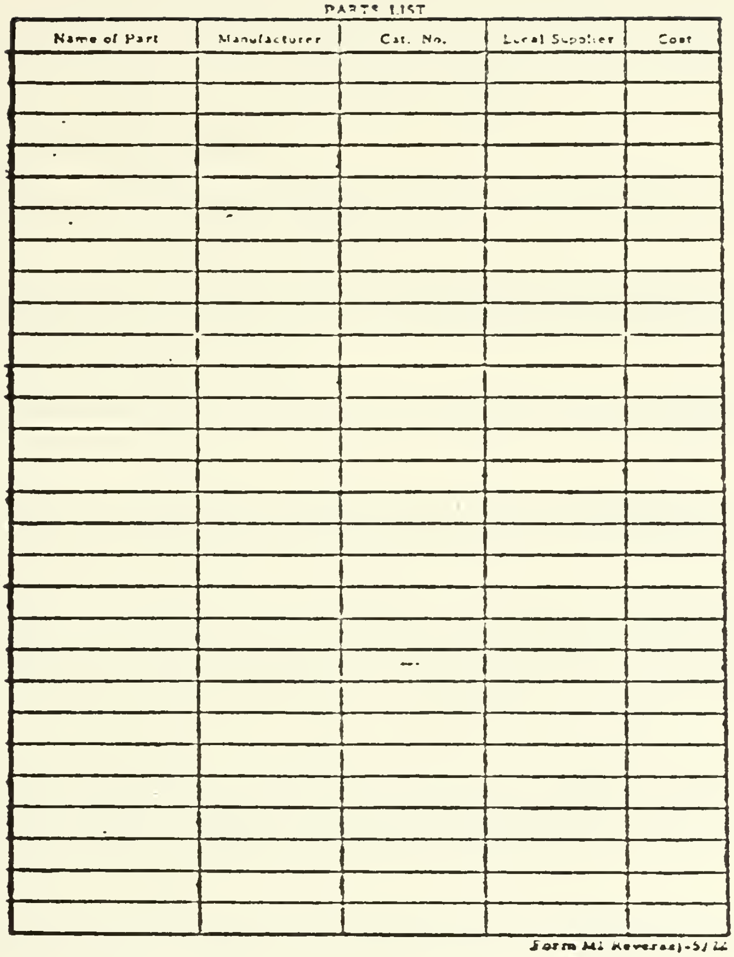
ADDITIONAL DATA FOR ELECTRIC MOTORS

	HP	FRAME	RPM	VOLTS	AMPS	PH
42221	0.5	M48	3450	115/230	6.8/3.4	1
42222	0.5	M48	3450	115/230	6.8/3.4	1
42223	0.5	M48	3450	115/230	6.8/3.4	1
42321	0.5	M48	3450	115/230	6.8/3.4	1
42322	0.5	M48	3450	115/230	6.8/3.4	1
42323	0.5	M48	3450	115/230	6.8/3.4	1
43321	100	445UP	1770	230/460	228/114	3
43322	100	445UP	1780	230/460	228/114	3
43421	30	A326UPT	1800	230/460	72.7/36.4	3
43422	30	A326UPT	1800	230/460	72.7/36.4	3
43423	30	A326UPT	1800	230/460	72.7/36.4	3
43424	30	A326UPT	1800	230/460	72.7/36.4	3
43521	5	213	3180	230/460	13.3/6.8	3
43522	5	213	3180	230/460	13.6/6.8	3
44121	0.75	56C	1725	230/460	3.1/1.55	3
44221	0.5	J56	1140	230/460	1.9/0.95	3
44222	0.17	F48	1725	115	3.4	1



EQUIPMENT REFERENCE DATA

Figure 1. Form M1, Equipment Reference Data



PARTS LIST

Name of Part	Manufacturer	Cat. No.	Local Supplier	Cost

Form M1 (Reverse)-5/72

Figure 2. Form M1 (Reverse), Parts List

not falling into one of these common categories, the data is entered in the block at the bottom of the form. The reverse side of Form M1 is for listing parts which are likely to be replaced. The basic purpose of Form M1 is to provide an accessible file of manufacturer's data for use in the event of a breakdown, or a proposed modification or replacement. The data on the form is also useful for generating an equipment inventory list and for planning a spare parts inventory.

The Maintenance Procedures

Each individual Maintenance Procedure (MP) is detailed on a numbered Maintenance Procedure Sheet (MPS), and:

1. Defines the maintenance task in terms that allow all concerned to know what is required, who must perform, estimate of time required and how often.

2. Standardizes the procedure and sequence for doing a job in the best known way.

3. Expedites the accomplishment of the task by stating the tools and materials needed and the safety precautions to be observed.

4. Provides a concise and complete work instruction to the maintenance personnel in the work space. The basic objective of the MPS is to be all inclusive. References to other publications are not required since availability of outside references other than instructions posted on or near the equipment cannot be assured.

For each equipment item in the plant, an MPS is included for each PM action. Since the maintenance requirements for parallel units are identical, the MPS is identified by the first four digits only and is applicable to all equipment items with those first four digits.

Each MPS has an additional two-character code. The first character specifies the required frequency for the particular maintenance according to the following list:

D - Daily
W - Weekly
M - Monthly
Q - Quarterly
S - Semiannually
A - Annually
R - As required

The second character is the designated number of MPs to be performed at the specified frequency.

Examples of some MPSs are included in Appendix II as Figures A-1 through A-18. A variety of MPSs are included to show the type and extent of the information included for different classes of equipment and maintenance actions. Each MPS contains:

1. The number, the descriptive title and the frequency of the maintenance action to be performed.
2. The skill level required to perform the maintenance.
3. An average time required to perform the maintenance, not including "make ready" and "put away" time.
4. The complete title, identification number, nameplate data and location of the equipment to avoid any ambiguity over which item of equipment is to be serviced.
5. The specific safety precautions to be observed when performing the maintenance action(s).
6. A list of tools, parts, materials and test equipment required.
7. The individual step-by-step instructions for the maintenance action. The instructions are specific, stating which type of lubricant to use, or what torque to use for tightening bolts, etc. The first instruction is always a repetition of the safety precautions.

A concise summary list of Maintenance Procedures (MPs) was generated to enable the Maintenance Engineer to rapidly identify the PM actions for each unit in the plant. Table 5 is a sample page of the summary list of Maintenance Procedures for the Lower Potomac Plant. This summary lists the operating unit, the description of the work to be performed for each Maintenance Procedure, the frequency of each PM task, the manpower requirement by skill and time in minutes for each PM task, and a key which initiates the schedule for performing each PM task. This key is simply the first scheduled week number, not necessarily January 1, but the week selected for PMMS start up, from which all other scheduled week numbers automatically follow.

1. Daily and weekly MPs are, of course, scheduled for every week from one to fifty-two.
2. For monthly MPs, add to the key number: 0, 4, 8, 13, 17, 21, 26, 30, 34, 39, 43, 47.

Table 5. SAMPLE FROM LIST OF MAINTENANCE PROCEDURES
(keyed to Maintenance Procedure Sheets [MPSs])

MP No.	Task Description	Skill/Minutes			Week No.
		1	2	3	
•1111	2 Bar Screen Mechanical Cleaner				
1111 D1	Lubricate bar screen		20	20	1
1111 D2	Inspect rake assembly and chain		25	15	1
1111 M1	Inspect counterweight shock absorbers			18	1
•1112	2 Motor, Bar Screen Cleaner				
1112 Q1	Clean motor and perform elec. inspection	18		18	1
1112 A1	Lubricate motor			30	1
•1113	2 Drive, Bar Screen Cleaner				
1113 W1	Check oil level			12	1
1113 Q1	Change oil		30		1
•1114	2 Control, Bar Screen Cleaner				
1114 A1	Clean and inspect controller	48		48	1
1114 A2	Clean and inspect remote control switch	30			1
•1121	3 Conveyor, Bar Screen Cleanings				
1121 W1	Inspect and lubricate conveyor		24		1
•1122	3 Motor, Conveyor, Bar Screen Cleanings				
1122 M1	Inspect drive belt(s) tension		12		3
1122 Q1	Clean motor and perform elec. inspection	18		18	3
1122 A1	Lubricate motor		-	24	3
•1123	3 Drive, Conveyor, Bar Screen Cleanings				
1123 W1	Check oil level			12	1
1123 S1	Change oil		30		3
•1124	3 Control, Conveyor, Bar Screen Cleanings				
1124 A1	Clean and inspect controller	48		48	3
1124 A2	Clean and inspect remote control switch	30			3
•1211	2 Grinder, Bar Screen Cleanings				
1211 W1	Lubricate grinder			18	1
1211 M1	Inspect drive belt(s) tension		18		2
1211 M2	Inspect grinder		90	180	2
•1212	2 Motor and Drive, Grinder, Bar Screen Cleanings				
1212 Q1	Clean motor and perform elec. inspection	18		18	6
1212 A1	Lubricate motor			30	6
•1213	2 Control, Grinder, Bar Screen Cleanings				
1213 A1	Clean and inspect controller	48		48	6
1213 A2	Clean and inspect remote control switch	30			6
•1311	3 Raw Wastewater Pump A				
1311 W1	Inspect packing gland adjustment		12		1
1311 R1	Renew packing		180		
1311 S1	Lubricate pump bearings			12	9
1311 S2	Lubricate coupling			6	9

•Equipment name

3. For quarterly MPs, add to the key number: 0, 13, 26, 39.

4. For semiannual MPs, add to the key number:. 0, 26.

5. For annual MPs, the key number is the scheduled week number.

The Preventive Maintenance (PM) Cyde Schedule

The PM actions are scheduled for each of the 52 weeks of the year. Table 6 is a sample listing of the Maintenance Procedures (MPs) scheduled for a particular week at the Lower Potomac Plant. The list is generally organized so that all MPs for a single unit in the plant are listed together for the purpose of assigning them to a single team at a time. Hence, the unit need be removed from service only once. Furthermore, the schedule was generated to group MPSs on the same unit, although of differing frequencies, during the same weeks.

The actual work assignment on a daily basis is left to the discretion of the foreman and plant management, since operational constraints, corrective maintenance work loads and employee absenteeism cannot be fully anticipated.

During one week in each quarter of the year, only daily and weekly PM is scheduled. The remaining time may be used by the plant to catch up on delayed preventive and corrective maintenance, and may also be used to allow for periods of high absenteeism (vacations, Easter week, Christmas week, etc.).

In addition to a list of MPs for each week of the year, the schedule lists the daily and weekly tasks separately. To augment the lists for each of the weeks, a master schedule displays the individual PM tasks for each operating unit in the plant for the entire year. This master schedule is part of the summary of Maintenance Procedures described previously (Table 5). An optional display in the form of a wall chart would enable the Maintenance Engineer to see at a glance what the PM work load will be, or alternately, to see when PM is to be performed on any particular unit.

The Recordkeeping System

The recordkeeping system of the PMMS consists of six forms. Forms M1 and M2 are permanent records for each item of equipment, containing reference data and cumulative maintenance data. Form M3 is a temporary record of preventive maintenance actions, and Forms M4, M5 and M6 are temporary records of corrective maintenance actions.

Table 6. EXAMPLE OF WEEKLY PM SCHEDULE

Week 1		
1111 M1	2133 M1	5222 Q1
1112 Q1	2133 Q1	5224 Q1
1112 A1	2242 M1	5225 Q1
1113 Q1	2332 M1	5312 M1
1114 A1	2332 M2	5564 M1
1114 A2	2332 M3	5571 M1
1334 M1	2332 Q1	5573 M1
2112 M1	2332 S1	5581 M1
2131 M1	2332 S2	5583 M1
2132 Q1	5221 M1	5711 Q1
2132 Q2	5221 M2	5712 Q1

Perform these plus all Daily and Weekly Maintenance Procedures (MPs), keyed to Maintenance Procedure Sheets (MPSs).

Form M1, "Equipment Reference Data," was described previously and is shown in Figures 1 and 2.

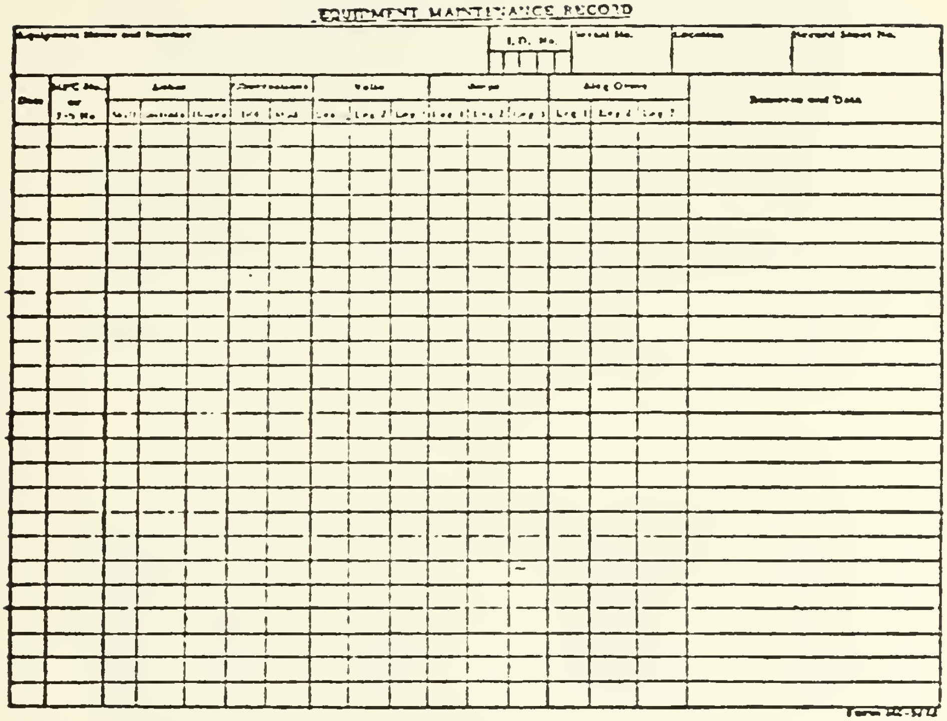
Form M2, the "Equipment Maintenance Record," provides an historical file of all PM and CM performed on a particular item of equipment. This 8-1/2 x 11-inch permanent record, shown in Figure 3, will be useful in the event of a breakdown or an impending breakdown, and for an examination of trends and of any indications of equipment deterioration with time. Each time a maintenance action is performed an entry is made on Form M2. The MPS number or the job number specifies, respectively, whether the action is PM or CM. The "Labor" entry is for recording the skill level, the initials of the mechanic and the actual manhours expended. The "Observations" entry is coded according to the list of Indicators and Modifiers, which is included as Table A-2. In addition to this coded entry, a descriptive statement can be made, when necessary, in the "Remarks and Data" column. The "Volts," "Amps" and "Megohms" entries are reserved for maintenance on electric motors.

Forms M3, M4 and M5 are temporary 5 x 8-inch records. Form M3, Figures 4 and 5, is a "Preventive Maintenance Work Record," which the mechanic uses while on the job to document that the PM work has been done and to record the labor expended and the measurements made. The checklist on Form M3 is used by the mechanic to indicate whether there was any indication of trouble during the routine PM and inspection. If any of the "Trouble" boxes are checked, the reverse side of Form M3, "Report of Trouble," is used by the mechanic to provide a detailed explanation.

Form M3X, a variation of Form M3, is shown in Figure 6. This format is used for daily and weekly actions, and conserves the amount of paper handled by having multiple entries on one form. In practice, this form is printed on the back of the 8-1/2 x 11-inch Maintenance Procedure Sheet, on heavy card stock, which is used repetitively until the available spaces are filled or until the card is mutilated. At that point, a replacement is made.

Whichever of the two Form M3 formats is used, and whether or not any of the "Trouble" boxes are checked, the data from Form M3 is transcribed onto the permanent Form M2. If there is no "Trouble," Form M3 can be discarded once the PM data have been recorded. If trouble has been spotted, Form M5 must be filled out to initiate CM action.

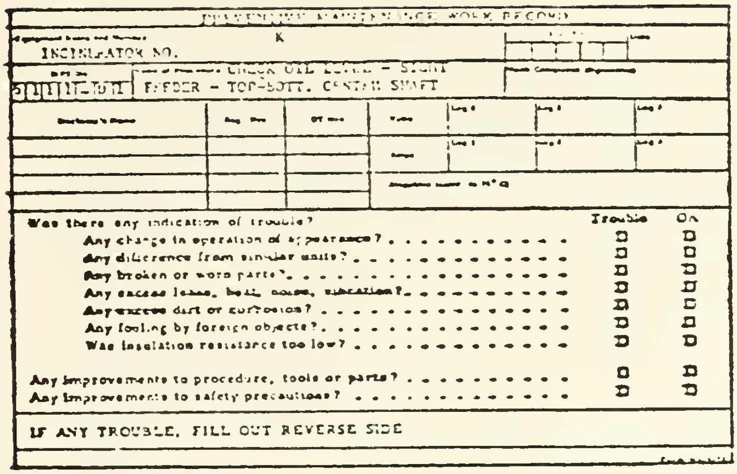
Form M4, the "Equipment Malfunction Report," shown in Figure 7, serves a similar purpose as the "Report of Trouble" side of M3, except that M4



EQUIPMENT MAINTENANCE RECORD

I. D. No.

Figure 3. Form M2, Equipment Maintenance Record



PREVENTIVE MAINTENANCE WORK RECORD

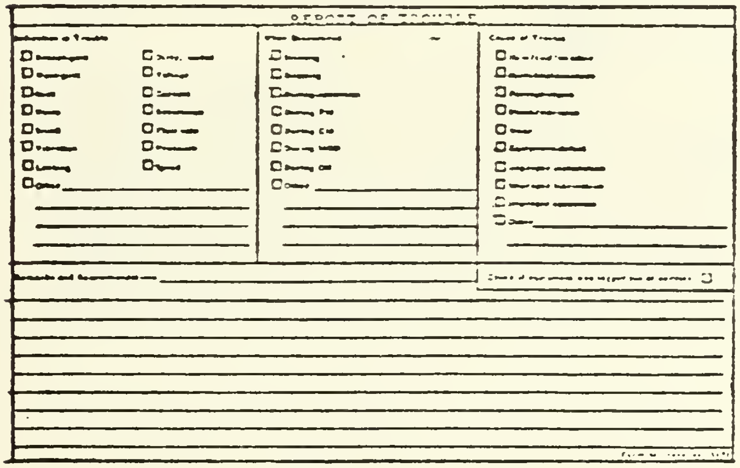
INCINERATOR NO. K

CHECK OIL LEVEL - SIGHT FEEDER - TOP-BOTT. CENTER SHAFT

	Trouble	OK
Was there any indication of trouble?		
Any change in operation or appearance?	☐	☐
Any difference from similar units?	☐	☐
Any broken or worn parts?	☐	☐
Any excess leaks, heat, noise, vibration?	☐	☐
Any excess dirt or corrosion?	☐	☐
Any fouling by foreign objects?	☐	☐
Was insulation resistance too low?	☐	☐
Any improvements to procedure, tools or parts?	☐	☐
Any improvements to safety precautions?	☐	☐

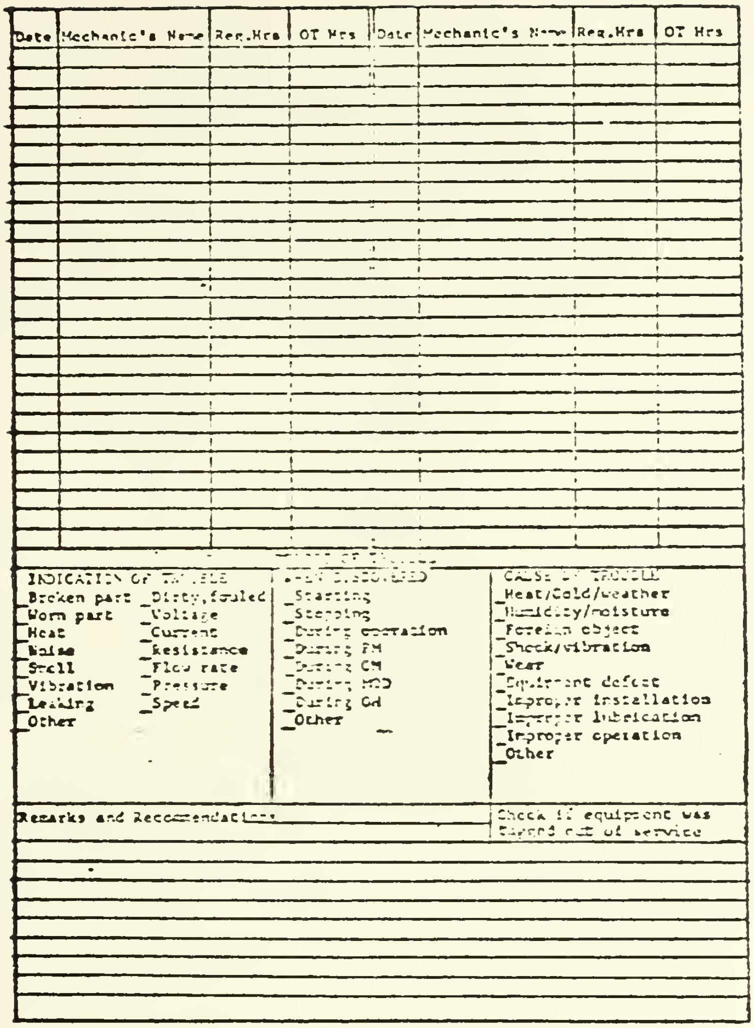
IF ANY TROUBLE, FILL OUT REVERSE SIDE

Figure 4. Form M3, Preventive Maintenance Work Record



REPORT OF TROUBLE

Figure 5. Form M3 (Reverse). Report of Trouble



Date	Mechanic's Name	Reg.Hrs	OT Hrs	Date	Mechanic's Name	Reg.Hrs	OT Hrs

TYPE OF TROUBLE

INDICATION OF TROUBLE
_Broken part
_Worn part
_Heat
_Noise
_Smell
_Vibration
_Leaking
_Other
_Dirty,fouled
_Voltage
_Current
_Resistance
_Flow rate
_Pressure
_Speed

WHEN DISCOVERED
_Starting
_Stopping
_During operation
_During PM
_During CM
_During MOD
_During OH
_Other

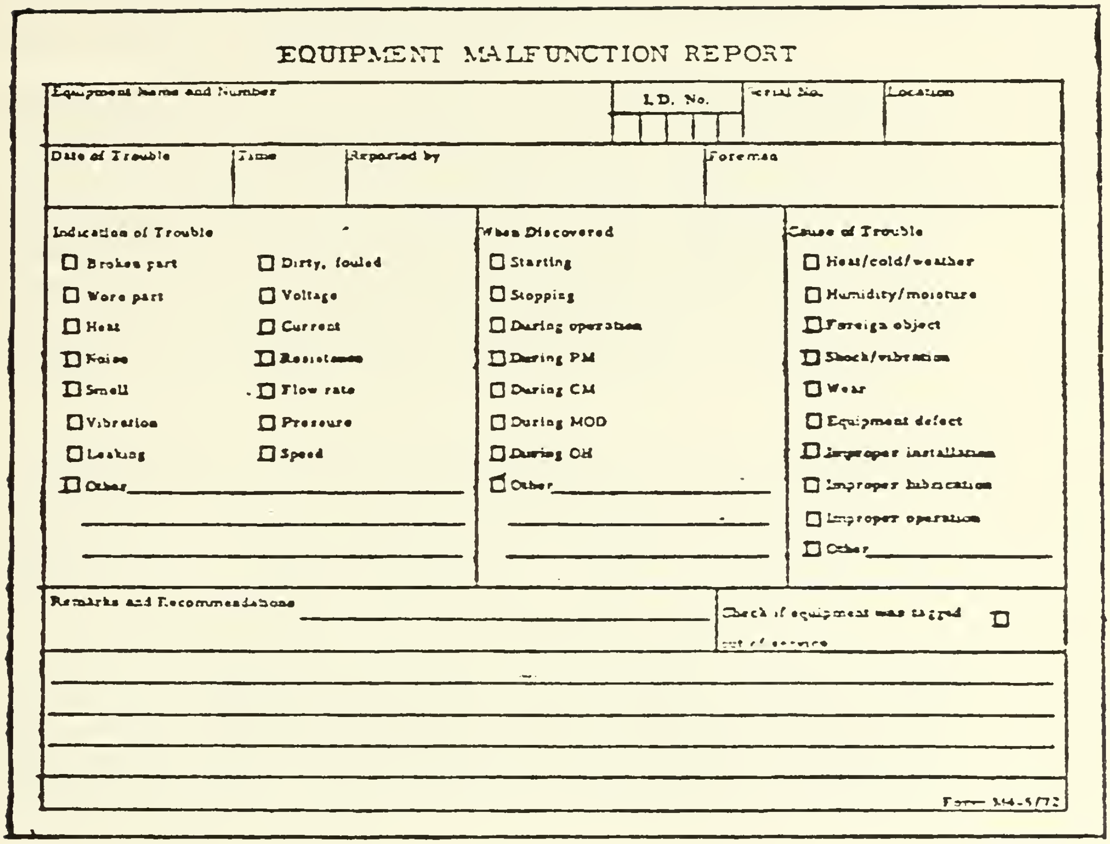
CAUSE OF TROUBLE
_Heat/Cold/weather
_Humidity/moisture
_Foreign object
_Shock/vibration
_Wear
_Equipment defect
_Improper installation
_Improper lubrication
_Improper operation
_Other

Remarks and Recommendations

Check if equipment was tagged out of service

Figure 6. Form M3X, Variation of Form M3*

*Summary of listing on reverse side of various maintenance procedure sheets.



EQUIPMENT MALFUNCTION REPORT

Equipment Name and Number	I.D. No.	Serial No.	Location

Date of Trouble	Time	Reported by	Foreman

Indication of Trouble

☐ Broken part
☐ Worn part
☐ Heat
☐ Noise
☐ Smell
☐ Vibration
☐ Leaking
☐ Other__________

☐ Dirty, fouled
☐ Voltage
☐ Current
☐ Resistance
☐ Flow rate
☐ Pressure
☐ Speed

When Discovered

☐ Starting
☐ Stopping
☐ During operation
☐ During PM
☐ During CM
☐ During MOD
☐ During OH
☐ Other__________

Cause of Trouble

☐ Heat/cold/weather
☐ Humidity/moisture
☐ Foreign object
☐ Shock/vibration
☐ Wear
☐ Equipment defect
☐ Improper installation
☐ Improper lubrication
☐ Improper operation
☐ Other__________

Remarks and Recommendations__________

Check if equipment was tagged out of service ☐

Form M4-5/72

Figure 7. Form M4, Equipment Malfunction Report

is intended for use by plant operators or anyone else noticing a malfunction (M3 is intended for use by maintenance mechanics while performing PM). Completed Forms M4 should, of course, be promptly delivered to the Maintenance Department. Pads of blank M4 Forms should be in convenient locations throughout the plant.

Forms M5 and M6, shown in Figures 8 and 9, are for initiating CM whenever the "Trouble" side of Form M3 or Form M4 has been received by the Maintenance Department. Form M5, a 5 x 8-inch "Corrective Maintenance Work Order," is prepared with cost and downtime estimates when analysis indicates that corrective action is required. This information is automatically reproduced, by the use of carbon or NCR-type paper, onto the top of Form M6. The combined forms then are signed, and a job number is issued, allowing the CM work to be initiated. At this point, the forms are separated; Form M5 is retained as an open work order, while Form M6 is used by the field maintenance personnel.

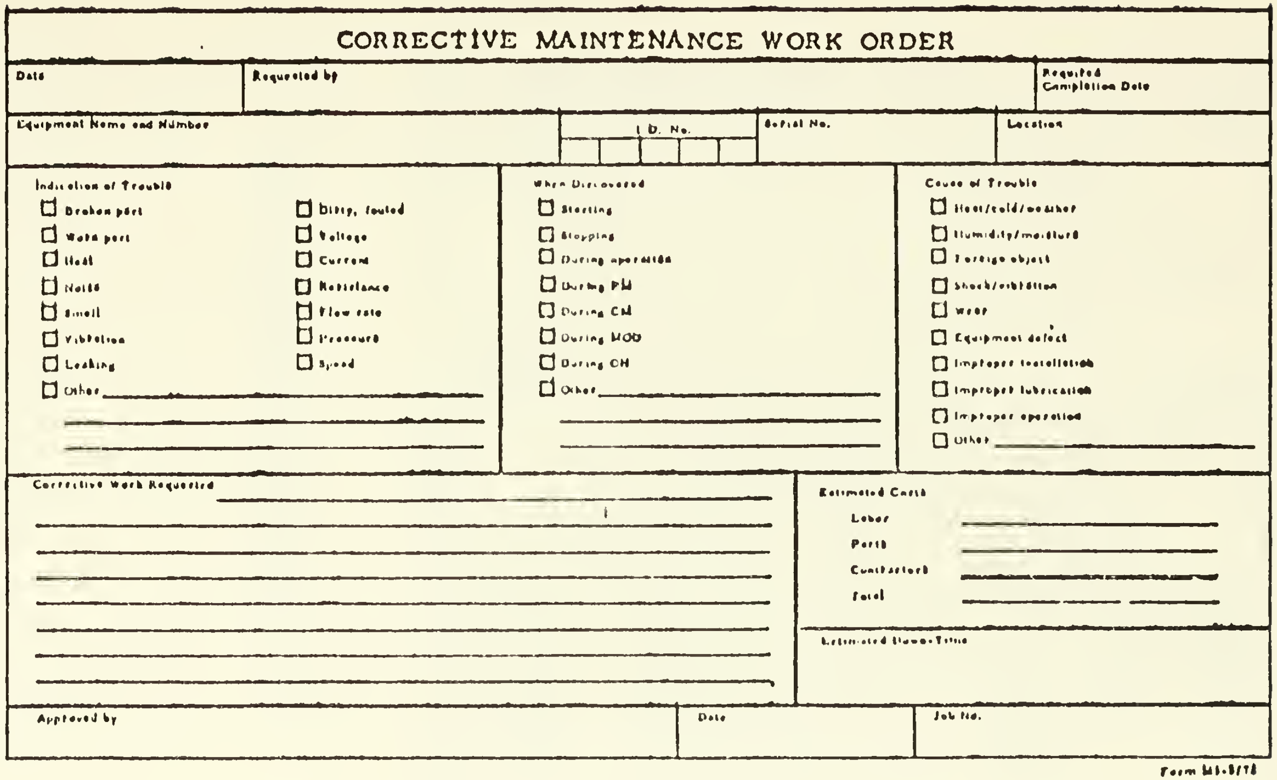
The lower half of M6, which is an 8-1/2 x 11-inch form, is used to record the labor, parts and materials used, descriptions and recommendations, equipment status and spare parts availability, and actual corrective maintenance costs and downtime. The maintenance foreman and the requestor sign off on the completed work. At this time, Form M5 may be discarded. An appropriate entry is made on Form M2, and Form M6 is kept in the permanent equipment file with the M1 and M2 forms.

The Recordkeeping System has been constructed to segregate the coding and the paperwork from the mechanics. The mechanics are given appropriate MPSs which explicitly identify both the equipment and procedure in common language. The mechanics fill out Forms M3 (or M4) and M6, which are designed as simple checklists. No other paperwork burden is placed upon the mechanics.

The Maintenance Data Feedback System

Form M7, shown as Figures 10 and 11, is a weekly maintenance summary report which is prepared by the Maintenance Technician for plant management. There are three parts to Form M7: a Work Load Summary and a Work Accomplished Summary on the front of the form, and a Corrective Maintenance Summary on the back.

The Work Load Summary corresponds to the balance sheet in a financial report. The new work load for the week is added to the old backlog for the total outstanding work; from this total is subtracted the work accomplished during the week to establish the new backlog for the following week.



CORRECTIVE MAINTENANCE WORK ORDER

Date
Requested by
Required Completion Date

Equipment Name and Number
I. D. No.
Serial No.
Location

Indication of Trouble
☐ Broken part
☐ Worn part
☐ Heat
☐ Noise
☐ Smell
☐ Vibration
☐ Leaking
☐ Other
☐ Dirty, fouled
☐ Voltage
☐ Current
☐ Resistance
☐ Flow rate
☐ Pressure
☐ Speed

When Discovered
☐ Starting
☐ Stopping
☐ During operation
☐ During PM
☐ During CM
☐ During MOD
☐ During OH
☐ Other

Cause of Trouble
☐ Heat/cold/weather
☐ Humidity/moisture
☐ Foreign object
☐ Shock/vibration
☐ Wear
☐ Equipment defect
☐ Improper installation
☐ Improper lubrication
☐ Improper operation
☐ Other

Corrective Work Requested

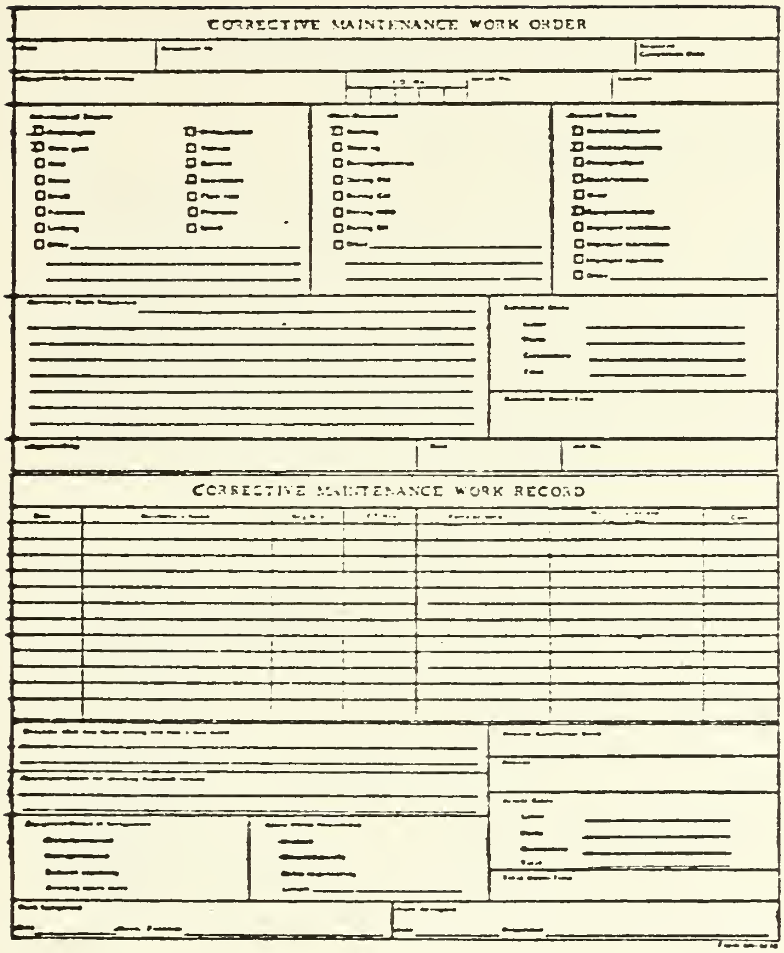
Estimated Costs
Labor
Parts
Contractors
Total

Estimated Down-Time

Approved by
Date
Job No.

Form M5-8/78

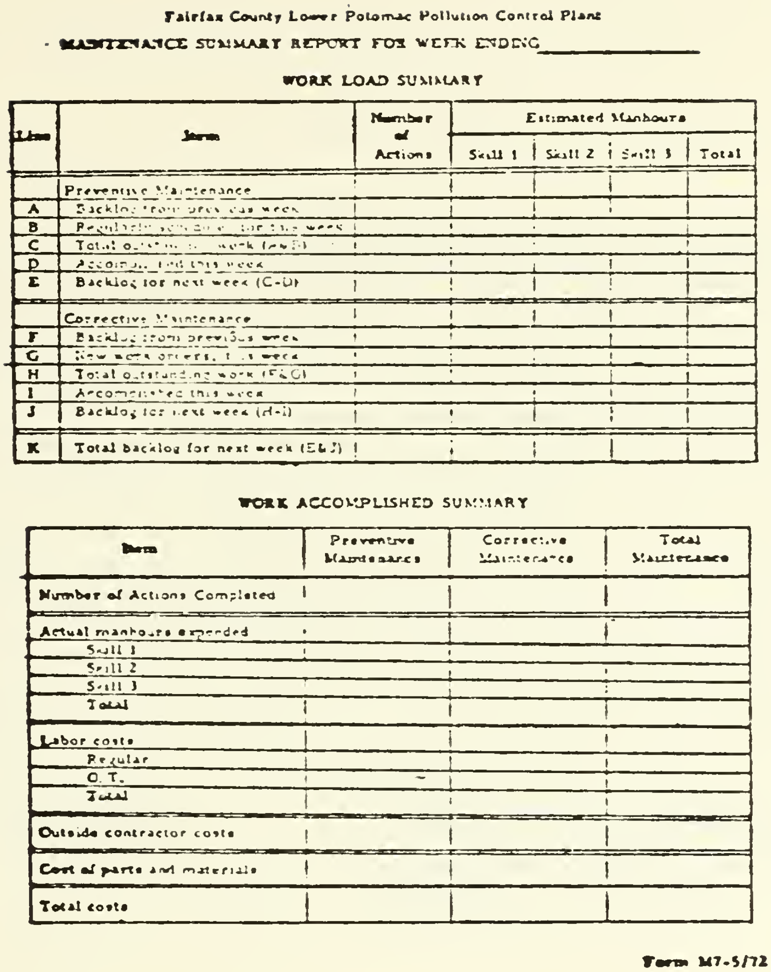
Figure 8. Form M5, Corrective Maintenance Work Order



CORRECTIVE MAINTENANCE WORK ORDER

CORRECTIVE MAINTENANCE WORK RECORD

Figure 9. Form M6, Corrective Maintenance Work Order and Work Record



Fairfax County Lower Potomac Pollution Control Plant

MAINTENANCE SUMMARY REPORT FOR WEEK ENDING ______________

WORK LOAD SUMMARY

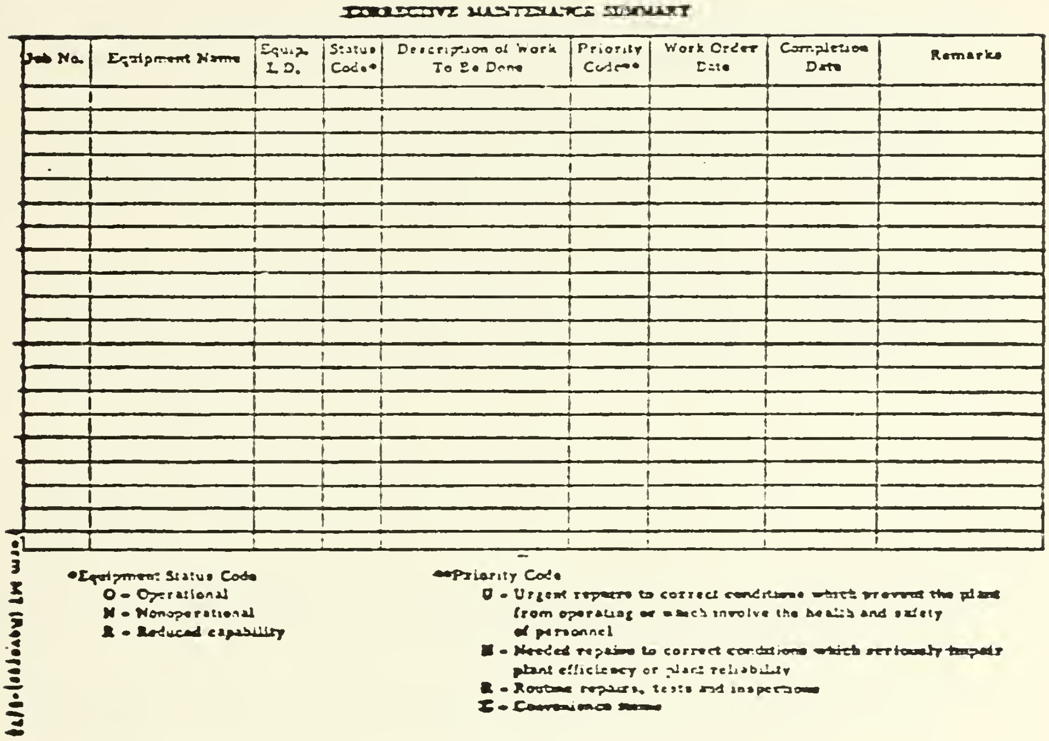
Line	Item	Number of Actions	Estimated Manhours			
			Skill 1	Skill 2	Skill 3	Total
	Preventive Maintenance					
A	Backlog from previous week					
B	Regularly scheduled for this week					
C	Total outstanding work (A+B)					
D	Accomplished this week					
E	Backlog for next week (C-D)					
	Corrective Maintenance					
F	Backlog from previous week					
G	New work orders, this week					
H	Total outstanding work (F&G)					
I	Accomplished this week					
J	Backlog for next week (H-I)					
K	Total backlog for next week (E&J)					

WORK ACCOMPLISHED SUMMARY

Item	Preventive Maintenance	Corrective Maintenance	Total Maintenance
Number of Actions Completed			
Actual manhours expended			
Skill 1			
Skill 2			
Skill 3			
Total			
Labor costs			
Regular			
O. T.			
Total			
Outside contractor costs			
Cost of parts and materials			
Total costs			

Form M7-5/72

Figure 10. Form M7, Weekly Maintenance Summary Report



CORRECTIVE MAINTENANCE SUMMARY

Job No.	Equipment Name	Equip. I.D.	Status Code*	Description of Work To Be Done	Priority Code**	Work Order Date	Completion Date	Remarks

*Equipment Status Code
- O - Operational
- N - Nonoperational
- R - Reduced capability

**Priority Code
- U - Urgent repairs to correct conditions which prevent the plant from operating or which involve the health and safety of personnel
- N - Needed repairs to correct conditions which seriously impair plant efficiency or plant reliability
- R - Routine repairs, tests and inspections
- C - Convenience items

Form M7 (Reverse)-8/78

Figure 11. Form M7 (Reverse), Corrective Maintenance Summary

A separate balance sheet is included for PM and for CM, and the new total backlog is shown. For the Work Load Summary, all manhours are expressed as "estimated" manhours.

The Work Accomplished Summary corresponds to the income statement in a financial report. The objective is to show the actual labor and the actual costs incurred during the week.

The Corrective Maintenance Summary lists all CM work orders (Form M5) that were outstanding at the beginning of the week and those that were initiated during the week. Those items that were completed during the week are noted by an entry in the "Completion Date" column. For plant management to decide which jobs to attack first, this Summary lists an Equipment Status Code and a Priority Code for each job. The "Remarks" column should be used for comments such as "awaiting spare parts."

The weekly maintenance summary report is prepared for plant management by the Maintenance Technician. The report is generated directly from the data in the Recordkeeping System. Aside from providing management with timely important data, the Feedback System is designed to relieve management of any paperwork burden.

SPECIAL CONSIDERATIONS IN THE PMMS

The Maintenance Technician

The permanent records, the Indicators and Modifiers Code, the PM Cycle Schedule, and the Equipment Configuration numbering system do not concern the mechanics in the performance of their work. All of the scheduling and monitoring for the PMMS is performed by a Maintenance Technician. His efforts may be strictly manual in smaller plants, or he may use computers or other data processing devices in medium-to-large plants.

The Technician position is essential to the successful implementation of the PMMS. It is the intention of the PMMS to remove the paperwork burden from the mechanics and from plant management, and to concentrate the paperwork and coordination of details upon the Technician.

The duties of the Maintenance Technician are:

1. To maintain and update a file for each item of equipment in the plant. The Technician records, on a continual basis, each preventive maintenance action taken. The data recorded includes the date, a code describing what was done, the initials and labor

category of the mechanic(s), the labor hours consumed, readings or measurements taken, and a coded entry of observations the mechanic will make regarding equipment condition. The Technician relieves the mechanics of any formal record-taking by transcribing his freestyle comments onto a permanent record. The Technician should therefore be familiar with equipment and with maintenance procedures to effectively communicate with the mechanics, and should be capable of using codes for recording and retrieval purposes.

2. To record corrective maintenance actions and equipment modifications in the equipment file. For corrective maintenance actions, the record will include labor hours, spare parts and purchased services, a cost for each item and for the total, the reasons for the breakdown, and suggestions for preventing similar breakdowns. The Technician is expected to understand and summarize the inputs from engineers and mechanics.

3. To maintain and update a file on equipment data, which will include type, model number, serial number, size, capacity, spare parts numbers, etc.

4. To prepare, on a weekly basis, the working copies of the MPSs (for planned PM actions) from a schedule and from a master file of sheets.

5. To retrieve and summarize data on equipment history, equipment condition, maintenance history, maintenance costs, and manpower requirements for the use of plant management. The Technician should be capable of providing meaningful summaries to relieve management of the burden of examining large quantities of data items.

6. To identify and implement improvements to the maintenance system.

Skills of Field Personnel

Three categories of labor are involved under the PMMS:

Skill 1—Electrician
Skill 2—Mechanic
Skill 3—Utility Man

Appendix I contains detailed job descriptions for these three labor categories.

In very small plants, a single individual generally performs all maintenance (possibly in addition to plant operations), so that this individual should have overall capability. Conversely, there is some trend today even in large plants to train maintenance personnel to perform both electrical and mechanical tasks, so that when a unit is taken out of service it may be completely attended to by a single man. This philosophy also aids in diagnosing malfunctions, where the precise cause of trouble is not readily apparent. This PMMS was developed to differentiate between skills; however, it is useful whether or not a wastewater treatment plant differentiates between skills.

For some plants, a separate instrumentation mechanic may be on the staff. To be most widely useful, this model PMMS did not assume that a separate skill existed for maintaining measurement devices and meters and recorders, but assigned these tasks as appropriate to either Skill 1 or Skill 2. In actual practice at the Lower Potomac Plant of Fairfax County, an Instrumentation Technician was added to the staff midway through the demonstration phase of the program. The PMMS was readily adaptable to this change without formally changing the PMMS paperwork. When the week's PM tasks were given to the maintenance foreman, he easily identified those appropriate to the Instrumentation Technician.

The Skill 3 category is labeled "Utility Man," and it indicates a lower level of experience than either Skill 1 or Skill 2. This distinction is extremely important in conserving the skilled manpower available for those tasks requiring the higher experience. Table A-3, the PM manpower requirement for the Lower Potomac Plant, shows that well over 50 percent of the total PM manhours is in the Skill 3 category, the category where personnel should be more available and of lower cost.

Consistent with the philosophy of this program to make the model PMMS most useful on a nationwide basis, no attempt was made to further break down Skill 3 into sub-skills perculiar to any plant or organization.

In actual practice at the Lower Potomac Plant, the bulk of the Skill 3 work has been accomplished by mechanics' helpers within the Maintenance Department. Several exceptions were made, with Operations personnel performing time-consuming tasks such as cleaning the sludge belt conveyors (prior to Skill 2 inspection and lubrication) and draining and cleaning primary settling tanks, secondary aeration tanks and chlorination contact chambers (prior to Skill 2 inspection).

Many of the Skill 3 tasks consist of routine repetitive PM actions requiring a minimum of judgement or special skills. At the option of the plant utilizing the PMMS, much of the Skill 3 workload may be accomplished

by plant operators, rather than by assigned personnel from the Maintenance Department. There are two sides to this question. In favor of such a division is the potentially significant cost and manpower savings, since Skill 3 tasks comprise well over 50 percent of the overall work load. Against such a division are:

1. A division is made in pride and responsibility; i.e., in the sense of "ownership" of equipment by regular maintenance mechanics which was evident at Lower Potomac.

2. An important feature of the routine repetitive PM actions is that maintenance personnel get around the plant on a regular daily basis and are therefore quick to spot any signs of impending trouble. Conversely, a shift operator may not be trained well enough to either notice the abnormality or to assign proper significance to it.

Judging by the tangible positive results at the Lower Potomac Plant, it is recommended that the Maintenance Department perform as much of the PMMS as is feasible within the very real constraints of the personnel available and the budget.

Cross Reference With Design Engineer's Code

When an existing, operating plant such as the Lower Potomac Plant installs a PMMS, the PMMS must take into account that the design engineer's equipment names and codes have become commonly used means for identifying equipment. The introduction of a new nomenclature via the PMMS does not change the commonly used nomenclature overnight. Hence, the PMMS must be structured so that the common names of equipment are retained in the lists, procedures, schedules, etc.

To correlate this dual nomenclature, a concise cross-reference list was prepared. Table A-4, for the Lower Potomac Plant, includes the design engineer's code for pumps, measurement transmitters and measurement receivers. Additional pumps in Area K are also included in Table A-4 for completeness.

Cross References for Remote Electrical Controls and Remote Alarm Indicators

In addition to measurement receivers (meters and recorders), which were covered in the previous section, there are two other instances where an equipment item may be quite remote from its functionally operating unit. One instance is the remote electrical controls. Table A-5 lists

the MPS numbers corresponding to the operating functional unit ID number, cross referenced to one or more remote controllers. Table A-6 cross references alarm operating functional numbers to one or more remote alarm indicators.

These cross-reference lists are to be used, of course, with the basic Equipment Configuration List, which provides data and location for each equipment item.

These cross references have been incorporated into the appropriate Maintenance Procedure Sheets. The remote electrical controllers are scheduled to be serviced at the same time as the PM on the process unit, while it is out of service. Observers are stationed at alarm indicators while malfunctions or abnormal conditions are simulated at the operating locations.

Insulation Resistance of Electric Motors

Since the insulation resistance of electric motors is very highly temperature dependent, a means for standardizing measured values is needed. There are two reasons why these insulation resistance measurements must be made when the motor is at ambient temperature: first, to avoid any appreciable temperature gradients, either spatial or temporal; and second, there is generally only the capability of measuring a constant ambient temperature. Once the insulation resistance at a measured ambient temperature is known, Figure 12 may be used to correct this value to a standard 70 deg F value.

Repainting of Plant Equipment

The PMMS includes a detailed MPS for repainting plant equipment and piping. No formal schedule or manhour estimate is associated with this MPS since requirements depend largely upon location, service, climate, etc.; and since the need for repainting is readily apparent.

Preventive Maintenance for Incineration

The sludge incineration and auxiliary process equipment require special attention in scheduling and performing preventive and corrective maintenance. The plant design provided redundant incinerator systems. Each incinerator system and its related equipment must be operated as a unit except for the induced draft fans which can be temporarily bypassed.

Table A-7 is a list of the sensitive equipment requiring special attention in the maintenance management system. Two categories of special preventive maintenance have been identified:

INSULATION RESISTANCE CORRECTION—multiply measured resistance correction factor

Minimum corrected resistance:

Class A insulation, 40 megohms
Class B insulation, 6 megohms

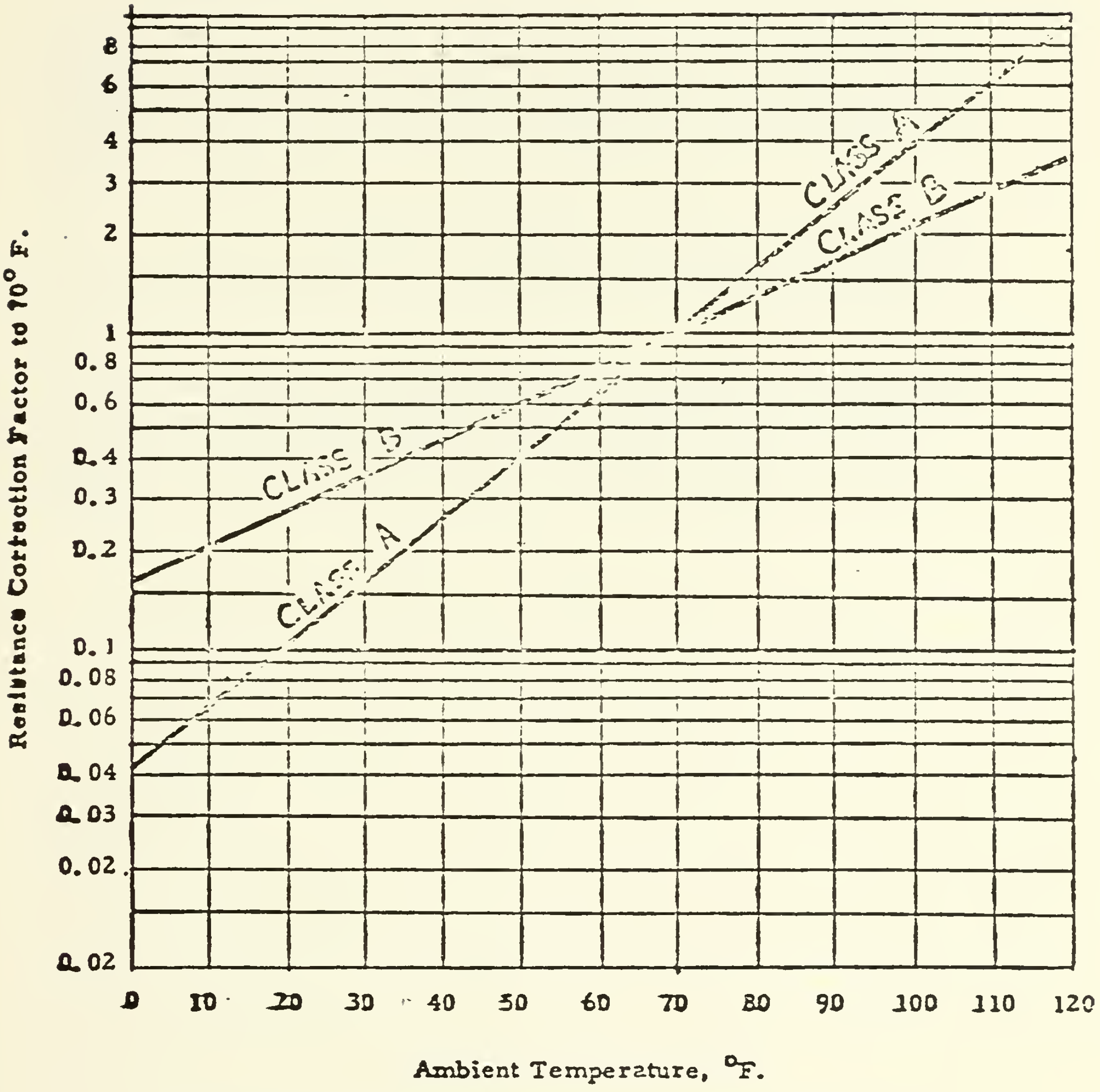


Figure 12. Corrections to Measured Insulation Resistance

1. Category A—The MP is to be performed without shutting down the equipment.
2. Category B—The MP is to be performed with the equipment taken out of service, but it must be scheduled to coincide with a shutdown of the entire incinerator by coordination between Maintenance and Operations.

Corrective maintenance may or may not require complete shut down of the affected incinerator and the auxiliary equipment. A judgement must be made by the Maintenance Department and coordinated with Operations. In addition, should one unit not be in service for an extended period, the unit and its auxiliary equipment should be exercised under full Maintenance/Operations coordination.

Table A-8 is a list of the MPSs in Category A, and Table A-9 is a list of the MPSs in Category B. Table A-9 should be used as a checklist to ensure that all scheduled MPSs are accomplished when the incinerator is shut down.

On each of the MPSs corresponding to Table A-8, there is a notation that, "This procedure is to be performed without shutting down the equipment." On the MPSs corresponding to Table A-9, the notation reads, "This procedure is to be performed only when the entire incinerator has been shut down."

APPENDIX B(94)

A. Seawater Conversion

The Combined Seawater Conversion and Power Plant (Desalination Plant) is comprised of a steam and condensate system, a power generating system and a seawater conversion system. The steam and condensate system includes three Erie City 120,000 pounds per hour high pressure steam boilers, the plant energy conversion source, and all interconnecting condensers, pumps, distribution lines, and condensate surge tanks that combine the three plant systems. The power generation system includes two Westinghouse 7,500KW turbine generators with low pressure process steam extraction supplying the evaporators' energy source. The seawater conversion system includes three Westinghouse 750,000 gallons per day multistage flash evaporators with brine recycle reheat and phosphate/acid scale control. Figure 5 provides a rudimentary schematic of the combined plant depicting major plant components.

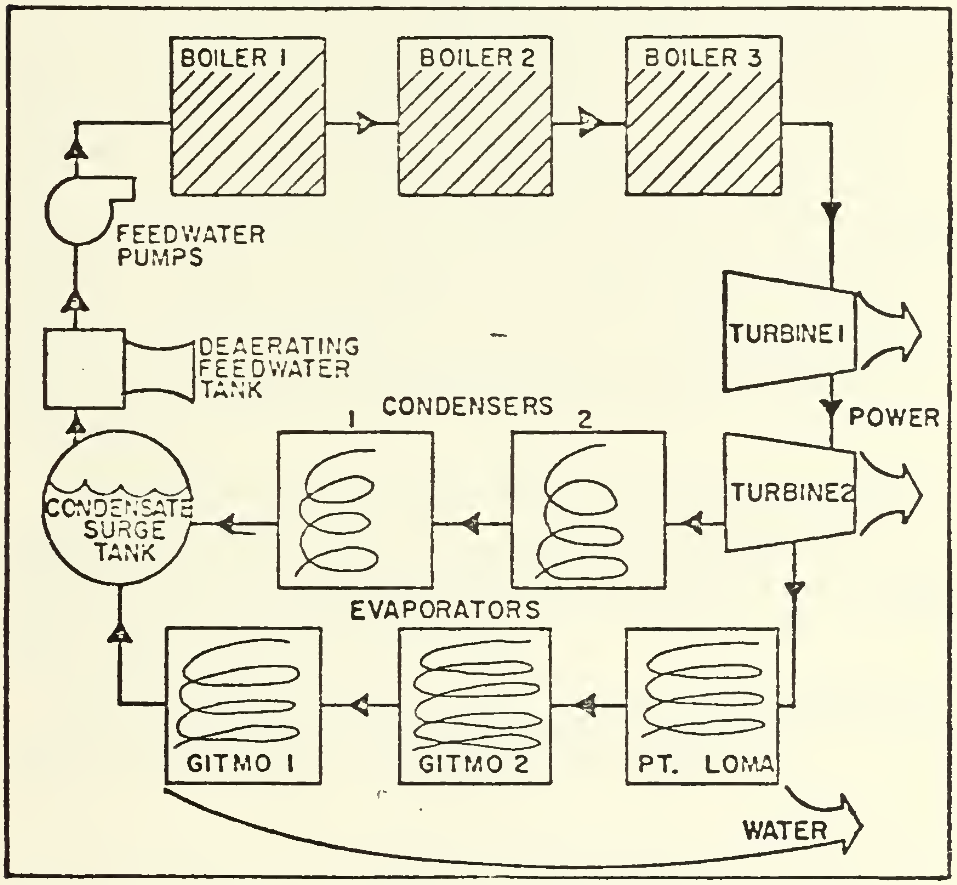


FIGURE 5. COMBINED SEAWATER CONVERSION & POWER PLANT.

It is appropriate now to analyze the seawater conversion system. The seawater conversion system serves four basic functions: (1) water production to meet Base consumption, (2) water quality control to ensure water suitable for domestic and industrial consumption, (3) efficiency control to provide maximum production with minimum consumption of energy and supplies, and (4) corrosion control to protect the government's investment in the plant. We shall discuss now how the seawater conversion system performs the four functions.

- PRODUCTION -

In discussing the water production function, it is helpful first to have a clear understanding of the heat and pressure relationship between liquids and gases as transformation from liquid-to-gas or gas-to-liquid takes place. The transformation is always accompanied by a transfer of heat called the LATENT HEAT OF VAPORIZATION. The magnitude of the heat of vaporization varies in direct proportion to the pressure of the liquid, i.e., the lower the pressure, the less heat required for vaporization. At a specified energy content, a pure liquid can exist in equilibrium with its vapor at but one pressure, its vapor pressure. This condition is reached naturally in the earth's water cycle as the sun adds heat to seawater through radiation until the latent heat of vaporization corresponding to atmospheric pressure is reached and water molecules escape from the sea as vapor. The limit is also reached through a sudden drop in pressure above the liquid. As the pressure drops, the liquid will transfer its heat corresponding to the equilibrium limit for the former pressure until it contains only enough internal energy to exist in equilibrium with the gas at the new lower pressure. The excess heat transferred become the LATENT HEAT OF VAPORIZATION for surrounding water molecules giving them the energy required to escape from the surface of the water and become a vapor. It can be seen, then, that through manipulating the energy content and pressure of a liquid, one can generate artificially the conditions required to transform a liquid to a gas and then back to a liquid again.

The Guantanamo Seawater Conversion System utilizes the principles stated in converting raw seawater into high quality potable water. In analyzing the production aspect of the seawater conversion system, it is evident from the preceding paragraph that three facilities are required: (1) the facility for manipulating the energy content of the fluid, (2) The facility for manipulating the pressure of the fluid, and (3) the vessel or chamber containing the process.

The Guantanamo Seawater Conversion units consist of two 15-stage and one 28-stage Multi-Stage Flash (MSF) evaporators. A general diagram of a MSF seawater conversion system is presented in Figure 6.

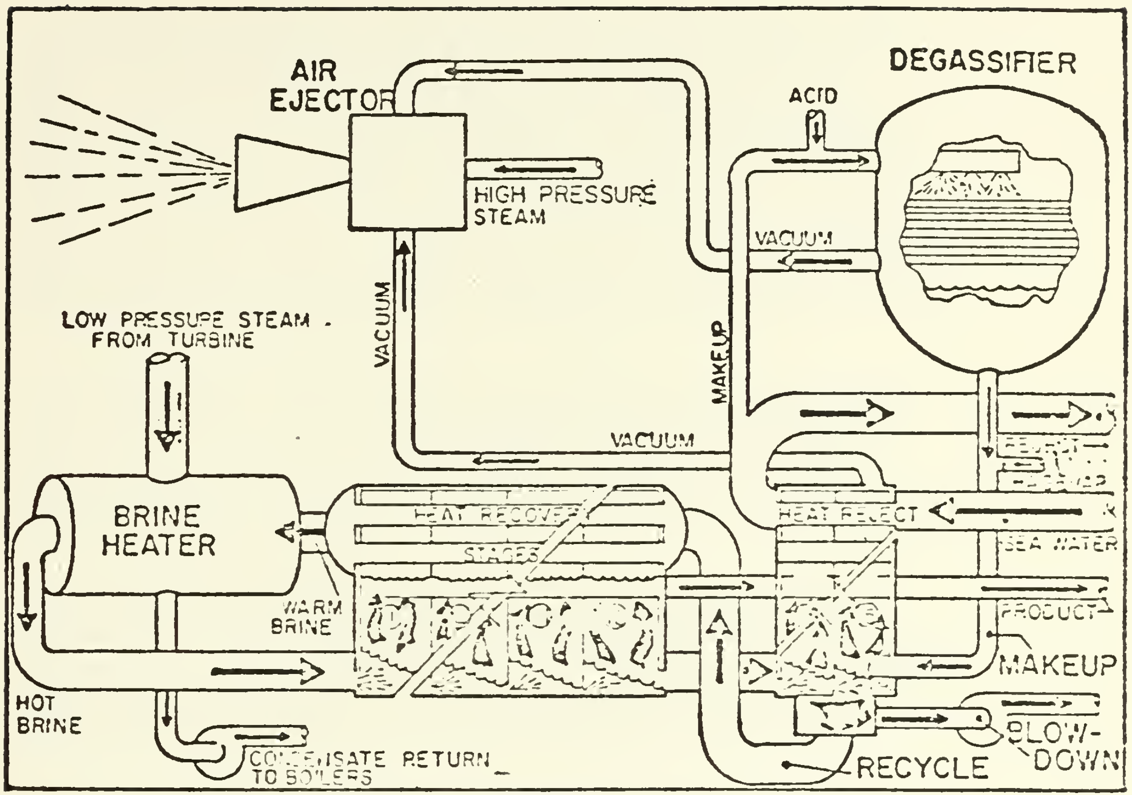


Figure 6. Seawater Conversion System

The evaporators receive raw seawater from Guantanamo Bay and the energy content of the cool seawater or brine is boosted through the Brine Reheating System, the pressure of the heated brine is reduced through the Evaporator Air Ejector System, and the process is contained by the Evaporator Vessel. Let us go first to the evaporator vessel.

Figure 7 provides a graphic view of the cross-section of a typical stage on one of the evaporators.

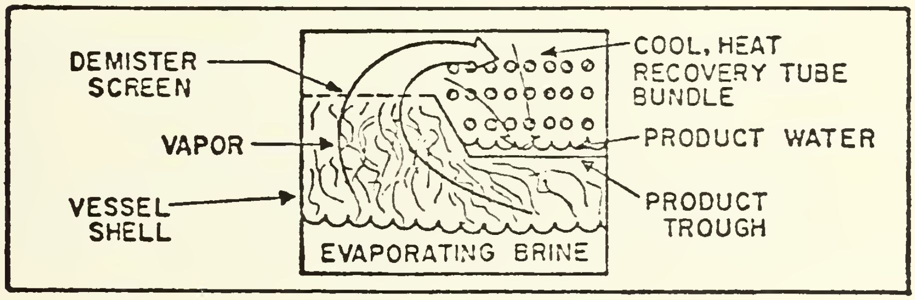


Figure 7. Evaporator Stage Cross Section

The vessel illustrated in Figure 7 has four basic components: (1) the vessel shell, (2) the demister screen, (3) the heat recovery tube bundle, and (4) the product trough. The vessel contains and aids the process whereby brine travels from stage to stage at incrementally decreasing pressures and releases its energy to achieve equilibrium at the new pressure. The excess energy becomes the heat of vaporization for surrounding water molecules which in turn "flash" into vapor thus the name "flash evaporator". The warm vapor travels to the upper section through the demister screen which removes mist. The vapor then encounters the cool heat recovery tubes, transfers its latent heat of vaporization to the tubes, and condenses. The condensate or distillate then drips down into the product water trough and is eventually pumped into the base water system for consumption.

The Brine Reheating System consists of a shell and tube heat exchanger which accepts "spent" steam extracted from the plant turbines (see Figure 5) and, using this as the energy source, transfers heat to the brine entering from the heat recovery tube bundle of Stage No. 1. The heated brine is then discharged into the lower section of the first and hottest stage, at a pressure lower than its equilibrium pressure, and the flashing process begins.

The Evaporator Air Ejector System (see Figure 6) consists of a high pressure steam nozzle assembly that takes suction of the 15th evaporator stage (the final and coolest stage) and vents to an inter- and after-condenser. The ejectors maintain 29 in. Hg vacuum in the 15th stage and preceding stages are maintained at incrementally higher pressures through the partial pressure of vapor flashing at the incrementally higher brine energy levels.

We can visualize now cool seawater entering the evaporator heat recovery tube bundles and proceeding through the evaporator continuously picking up the heat of vaporization of the condensing product. A final boost of heat to the brine is received in the "brine heater". Then we see the hot brine begin its odyssey from the 1st stage to the 15th stage at incrementally decreasing pressures, continually attempting to achieve equilibrium in each stage through the transfer of heat and flashing into vapor. We then see the vapor giving up its heat of vaporization to the heat recovery tubes and condensing to form the required product.

- QUALITY CONTROL -

Through the facilities discussed, the Guantanamo Seawater Conversion System fulfills the function of water production. Second only to production is the function of product water "quality control".

The physical facility for providing product quality control in the evaporators is the demister screens as was shown in Figure 7. The screens physically separate the condensing product water from the flashing brine and stop the transfer of any brine droplets carried with the water vapor. Chemical treatment of the makeup water entering the evaporator with

an anti-foaming agent further enhances quality control. The anti-foaming agent, as its name implies, deters foaming in the hot brine and reduces the liquid carryover to the demister screen. The result of these quality control measures is the production of distillate free of the chlorides of calcium, magnesium, and sodium which are so prevalent in seawater. Needless to say, the early indication of problems developing in the evaporator is an increase in chlorides in the product water.

- EFFICIENCY -

When production and quality control are ensured, one naturally concerns himself with the efficiency of the system. In its simplest terms the efficiency of the evaporator becomes the effectiveness of heat transfer to the brine and the ability to recycle waste heat. The Guantanamo systems recycle waste heat through the "brine recycle system" and maintain heat transfer effectiveness through the "acid feed and Hagevap systems".

Figure 6 shows raw seawater from GTMO Bay entering the 15th stage tube bundle and proceeding through stages 14 and 13 consecutively while "reclaiming" the latent heat of vaporization from the flashing brine. At the discharge of stage 13 some of the seawater is channeled into the makeup line (to be used to "make-up" for the brine evaporated into product water and brine discharged to reduce salinity concentrations (blowdown)) and the rest is rejected to waste. Because most of the water is rejected to waste, the 13th, 14th and 15th stages are termed "heat reject stages".

The makeup water then proceeds through the makeup line back to the lower section of stage 15 where it is mixed with the returning highly saline brine for dilution. The mixture is then pumped out of stage 15 into the heat recovery bundle of stage 12 to continue its odyssey through the evaporator. Thus the waste energy contained in the brine in the 15th stage is recycled.

The method through which waste energy is recycled and the effect of recycle on water chemistry and energy/chemical consumption is of interest in that it is considered a prime source of possible increases in evaporator efficiency and consequent reduction in water production costs. In this respect, blowdown has a major effect on evaporator efficiency. As the water vapor evaporates from the heated brine leaving behind mineral residue the total solids and chloride content of the recycling brine increases proportionally. Continuous blowdown is required to discharge concentrated brine and replace it with fresh makeup water thus maintaining the recycle chloride concentration at an acceptable level. Experimental analysis has proven that the optimum chloride level for recycle at which the evaporator will operate most effectively is approximately 30,000 parts per million (PPM). Referring back to Figure 3 it is seen that Guantanamo seawater has 21,300 PPM chlorides. The ratio of recycle chlorides to Guantanamo seawater chlorides, then, is 1.5 to 1. This ratio, which is known as the Concentration Factor (CF), provides an indicator of salinity buildup in

the evaporators and guides the blowdown requirement. Based on experimental data blowdown is plotted against concentration factor in Figure 8.

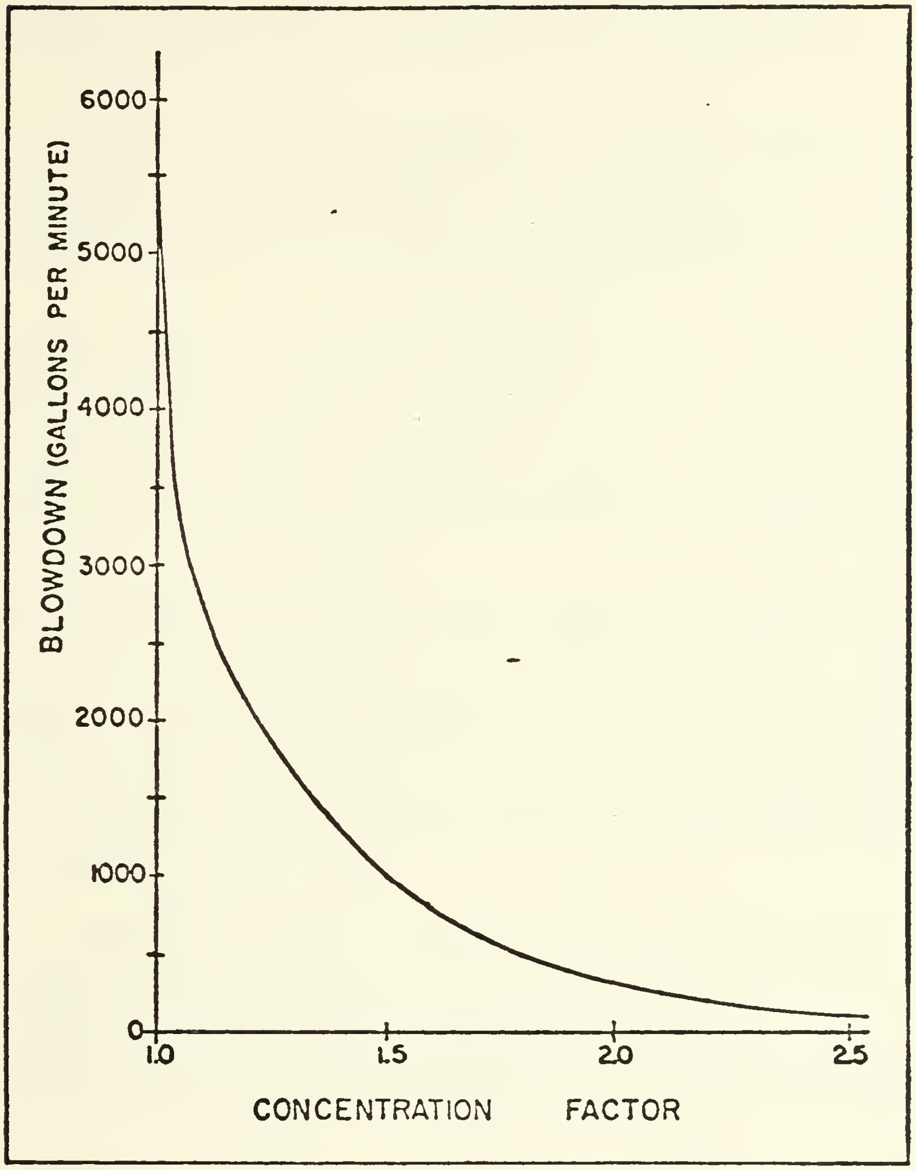


FIGURE 8. BLOWDOWN VS. CONCENTRATION FACTOR.

It is seen from Figure 8 that blowdown decreases exponentially as CF increases. Using the 30,000 PPM upper limit on our chloride level in recycle brine the CF can be increased above the 1.5 level only by diluting the 21,000 PPM chloride seawater makeup. Obviously, by decreasing the makeup chlorides, the CF can be increased to a theoretical limit of infinity (blowdown = 0) with a makeup chloride level of zero (pure H_2O).

The dilution of evaporator seawater makeup with a low chloride water resource is an excellent application for wastewater reclamation. Low chloride treated wastewater can be injected into the evaporator makeup line to allow a significant increase in the concentration factor and resultant reduction in blowdown without increasing the 30,000 PPM recycle salinity concentration. The reduced blowdown will result in substantial energy and chemical savings for the evaporators.

Let us now look at the methods of maintaining heat transfer effectiveness in the Guantanamo evaporators. As is seen in Figure 3, seawater contains copious amounts of hardness in the form of soluble calcium and magnesium chlorides, carbonates, and sulfates. At high temperatures, these soluble salts will tend to bake onto evaporator heat transfer surfaces and form a hard scale. The hard scale, in turn, reduces the heat transfer coefficient of the heat transfer surfaces and consequently reduces the efficiency and capacity of the evaporator. The problem becomes one of detering the formation of scale in the evaporators.

It has been standard practice for decades in the steam power industry to treat boiler feedwater with phosphates to fight hard scale. The phosphate will react with the soluble calcium or magnesium salt and form a harmless insoluble sludge easily removable from the system. By taking this principle one step further and adapting it to seawater, the Guantanamo seawater makeup is treated with a phosphate compound known as HAGEVAP. Figure 6 shows the Hagevap feed system feeding the makeup line to the 15th stage where the calcium and magnesium salts are at their greatest concentrations. Subsequently, the treated brine proceeds to the 12th stage heat recovery tube bundle to begin its journey to the 1st stage and brine heater at ever increasing temperatures but with the phosphate protection against hard scale.

To enhance the phosphate treatment an additional chemical must be added to carry away the insoluble sludge. The sludge formed by the phosphate treatment tends to collect on the heat transfer surfaces and reduce efficiency and capacity in the evaporators after about a week of operation. To remove the adhering sludge the "evaporator acid feed system" is activated to inject sulphuric acid into the evaporator makeup. The acid feed system is simply an acid storage tank with a small pump and discharge line connected to the seawater makeup line shown in Figure 6.

Through the use of the brine recycle system waste heat and chemicals are recovered and through the use of the Hagevap and acid feed systems heat transfer effectiveness is maintained. The problem of lagging evaporators efficiency now becomes one of maintenance of these three systems.

-CORROSION CONTROL-

Let us turn now to the system function that presents the desalination industry with the most problems and, when ineffective, adversely affects production, quality control, and efficiency of the evaporator: Corrosion control.

Corrosion may be defined as ". . .the destruction or deterioration of metal by direct chemical or electrochemical reaction with its environment". We know that certain metals naturally resist corrosion such as gold, silver, or copper; therefore, the corrosion control function becomes one of selecting the metals for evaporator construction that will least tend to corrode, and to provide a system that will deter the metal's direct reaction with its environment. Needless to say, the corrosion resistant metals listed would make evaporator construction using these metals too expensive for practical use. We are faced, then, with the problem of constructing our evaporator with the inexpensive alloys of iron and providing facilities for detering the electrochemical reaction of iron with seawater.

The element iron when placed in contact with water tends to go into the solution in the form of electrically charged iron ions, but, since the solution must remain electrically neutral, these positive ions can enter the solution only if an equivalent number of positive ions of some other element are somehow displaced. Thus, when iron is placed in water the element immediately plated out is HYDROGEN which gathers on the iron surface as a thin invisible film. This is the typical "primary reaction of corrosion" and may be expressed as follows:

$$\underset{\text{Metal}}{Fe} \quad + \quad \underset{\text{Ions}}{2H^{+}} \quad \rightleftharpoons \quad \underset{\text{Ion}}{Fe^{++}} \quad + \quad \underset{\text{Atoms}}{2H}$$

The activity of this primary reaction will always be directly proportional to the hydrogen ion activity in the water. . .the greater the hydrogen ion activity in the water, the more ions there are to plate out and the more iron that goes into solution. Hydorgen ion activity is normally measured in terms of pH factor. A high pH factor indicates a low hydrogen ion activity and vice versa. Thus, to reduce the hydrogen ion activity in water and deter the primary reaction of corrosion, one must increase the pH factor.

After the primary reaction, corrosion proceeds with the destruction of the hydrogen film. This happens in two ways: (1) In basic water (pH above 7), the hydrogen combines with oxygen present in solution to form water, or (2) in acidic water (pH below 7) it escapes as bubbles of hydrogen gas. This brings us to the "secondary reaction of corrosion" which may be expressed as follows:

$$\underset{\text{Atoms}}{2H} \quad + \quad \underset{\text{Dissolved}}{1/2\text{-}O_2} \quad \longrightarrow \quad \underset{\text{Liquid}}{H_2O}$$

or

$$\underset{\text{Atoms}}{2H} \quad \longrightarrow \quad \underset{\text{Gas}}{H_2}$$

These permit the primary reaction to proceed with the accumulation in the solution of Fe+++ which is oxidized and precipitated as rust as follows:

$$2Fe^{+++} + 1/2 - O_2 + H_2O \longrightarrow \underset{\text{Insoluble ferric hydroxide (rust)}}{2Fe^{+++} + 2OH^-}$$

The secondary reaction may be deterred by simply removing the dissolved oxygen from the water and denying the plated hydrogen atoms transportation back into solution.

From the preceding analysis it is seen that the corrosion control function becomes one of maintaining a high PH factor and/or removing dissolved oxygen from the water. Guantanamo seawater has a pH factor of 7.6 which is a basic pH and reasonably high. The addition of caustic chemicals such as sodium hydroxide to raise the pH factor of the seawater would interfere, with the acid treatment previously discussed; therefore, caustic feed is not used in Guantanamo to deter corrosion.

Our corrosion control function is one of deterring the secondary corrosion reaction through the removal of dissolved oxygen from the makeup water. The oxygen is removed through a "vacuum degassifier" which heats the makeup water with steam and exposes it to vacuum conditions while cascading it through "scrubbing" trays. The degassifier utilizes the principles of "Henry's Law" and "Dalton's Law" which imply that the solubility of a gas in a solution is directly proportional to its pressure and inversely proportional to its temperature. The gases removed in the degassifier are vented to the evaporator's 15th stage and subsequently removed by the air ejector. Refer to Figure 6 and note that the degassifier is located in the makeup line upstream from the 15th stage.

BIBLIOGRAPHY

1. John W. Sarappo, "Contract Maintenance: Its Place in Chemical Plants," Chemical Engineering, Vol. 76, No. 23 (November 17, 1969), p. 264.

2. R.L. Oliverson, "Contract Maintenance - Pro and Con," Plant Engineering, Vol. 26, No. 11 (June 1, 1972), p. 50.

3. Ibid., p. 51.

4. Willard Thomas Price, An Analysis of Contract Maintenance Versus Force Account Maintenance in Public Works (Pittsburgh, Pennsylvania: Graduate Center for Public Works Engineering and Administration, University of Pittsburgh, 1970).

5. Oliverson, Op. Cit., p. 47.

6. Sarappo, Op. Cit., p. 270.

7. G.E. Rohrmann, "Contract Maintenance in a Refinery," Chemical Engineering Progress, Vol. 67, No. 4 (April, 1971), p. 43.

8. Ronald J. Grey, "An Owner Looks at a Maintenance Contract," Hydrocarbon Processing, Vol. 52, No. 1 (January, 1973), p. 65.

9. R.L. Oliverson, "How NASA's Michoud Base Meets Maintenance Needs on a Contract Basis," Plant Engineering, Vol. 24, No. 17 (August 20, 1970), p. 62.

10. F.P. Flesca, "Can You Motivate Contract Maintenance Workers?", Hydrocarbon Processing, Vol. 50, No. 1 (January, 1971), p. 87.

11. "Terotechnology - The Package Deal Which Cuts Losses," The Engineer, Vol. 233, No. 6027 (September 9, 1971), p. 50.

12. Arthur Corsano, "Recommendations for an Improved Maintenance Management System for the Department of Public Works, Pittsburgh, Pennsylvania" (unpublished M.S. Thesis, Department of Civil Engineering, School of Engineering and Department of Public Works, Graduate School of Public and International Affairs, University of Pittsburgh, 1974), p. 110.

13. James L. Martin, "Contract Vs. In-House Building Maintenance," The APWA Reporter, Vol. 41, No. 7 (July, 1974), pp. 18-19.

14. Oliverson, Op. Cit., pp. 62-65.

15. Ibid., p. 65.

16. Rohrmann, Op. Cit., p. 46.

17. Grey, Op. Cit., pp. 65-67.

18. Flesca, Op. Cit., pp. 87-89.

19. F.P. Flesca, "Beat the Service Personnel Squeeze with Contract Maintenance," Plant Engineering, Vol. 25, No. 4 (February 18, 1971), p. 80.

20. Report of the Formal Board of Investigation (Guantanamo Bay, Cuba: U.S. Naval Station, 1972), unpublished.

21. Letter from Jack C. Rickels, Captain, Civil Engineer Corps, U.S. Navy, Public Works Officer, U.S. Naval Station, Guantanamo Bay, Cuba, dated 29 November, 1974.

22. Maintenance Management of Public Works and Public Utilities, NAVFAC MO-321 (Washington: Department of Defense, July, 1968), p. 7.

23. Corsano, Op. Cit., pp. 19-29.

24. Ibid., pp. 13-19.

25. William C. Hall, "Is There Man or Beast in Maintenance Management?", Navy Civil Engineer, Vol. 15, No. 2 (Summer, 1974), pp. 38-40.

26. R.B. McGuire, "Improve Cost Control Effectiveness with Systematic Maintenance Job Planning," Plant Engineering, Vol. 28, No. 22 (October 31, 1974), pp. 59-60.

27. Donald H. Sargent, A Planned Maintenance Management System for Municipal Wastewater Treatment Plants, EPA-600/2-73-004 (Washington, D.C.: EPA, November, 1973).

28. Maintenance Management of Public Works and Public Utilities, Op. Cit., pp. 7-11.

29. Price, Op. Cit., p. 109.

30. Maintenance Management of Public Works and Public Utilities, Op. Cit., p. 9.

31. Herbert A. Simon, The New Science of Management Decision (New York: Harper and Brothers, 1960), p. 50.

32. George T. Heery, "Construction Management Defined," The Military Engineer, Vol. 66, No. 430 (March - April, 1974), p. 86.

33. Sargent, Op. Cit., p. ii.

34. Corsano, Op Cit., pp. 90-117.

35. Joseph Valentine Francis Clay III, "Determination and Justification of Real Property Maintenance Requirements in the Navy" (unpublished M.S. Thesis, Department of Civil Engineering, School of Engineering and Department of Public Works, Graduate School of Public and International Affairs, University of Pittsburgh, 1974).

36. Frederick S. Hillier and Gerald J. Lieberman, Introduction to Operations Research (San Francisco: Holden-Day, Inc., 1967), p. 17.

37. NAVFAC Construction Quality Control Manual, NAVFAC P-445 (Alexandria, Virginia: Department of the Navy, Naval Facilities Engineering Command, January, 1974), p. 1-1.

38. Donald Wittschiebe, "Controlling Construction Quality," The APWA Reporter, Vol. 41, No. 10 (October, 1974), p. 12.

39. Ibid., p. 13.

40. NAVFAC Construction Quality Control Manual, Op. Cit., p. 1-2.

41. Ibid., p. 1-3.

42. McGuire, Op. Cit., p. 59.

43. Contract No. N66144-74C-0005 Operation and Maintenance of Desalinization and Power Plant No. 4 (Guan-

tanamo Bay, Cuba: U.S. Naval Base, 1974), unpublished.

44. Facilities Project Manual, OPNAV Instruction 11010.2B (Washington: Department of the Navy, 2 July, 1971), p. 3-1.

45. Hillier, Op. Cit., p. 16.

46. William L. Etter, "Benjamin Franklin and Prudential Algebra," The Journal for the American Institute for Decision Sciences, Vol. 5, no. 1 (January, 1974), pp. 145-146.

47. E.H. Bowman, "Consistency and Optimality in Managerial Decision Making," Management Science, Vol. 9, No. 2 (January, 1963), pp. 310-321.

48. Ibid., p. 316.

49. Simon, Op. Cit., p. 18.

50. J. Pratt, H. Raiffa, and R.O. Schlaifer, Introduction to Statistical Decision Theory (New York: McGraw-Hill Book Company, 1965).

51. Victor A. Thompson, Decision Theory, Pure and Applied (New York: General Learning Press, 1971), p. 4.

52. Pratt, et. al., Op. Cit., p. 4.1.2.

53. C.B. McGuire and Roy Radner, ed., Decision and Organization," Exposition of the Theory of Choice Under Uncertainty, by Kenneth J. Arrow" (Amsterdam: North-Holland Publishing Co., 1972), Chapter 6.

54. George P. Huber, "Methods for Quantifying Subjective Probabilities and Multi-Attribute Utilities," The Journal for the American Institute for Decision Sciences, Vol. 5, No. 3 (July, 1974), p. 445.

55. Kenneth R. MacCrimmon and John K. Siu, "Making Trade-Offs," The Journal for the American Institute for Decision Sciences, Vol. 5, No. 4 (October, 1974), pp. 680-681.

56. Alfred Skolnick, "A Structure and Scoring Method for Judging Alternatives," IEEE Transactions on Engineering Management, Vol. EM-16, No. 2 (May, 1969) pp. 72-83.

57. Ibid., p. 75.

58. Grant Fulgham, *The Multistage Flash Distillation Process* (Pittsburgh, Pa: University of Pittsburgh, 1974), unpublished.

59. Huber, Op. Cit., p. 450.

60. Ibid., pp. 430-431.

61. Corsano, Op. Cit., pp. 90-108.

62. *Maintenance Management of Public Works and Public Utilities*, Op. Cit., p. 37.

63. Corsano, Op. Cit., pp. 112-140.

64. Ibid., p. 110.

65. Leonard J. Savage, "Personal Probabilities," *Journal of the American Statistical Association*, Vol. 66, No. 336 (December, 1971), p. 798.

66. F.M. Scherer, "The Theory of Contractual Incentives For Cost Reduction," *Quarterly Journal of Economics*, Vol. 78, No. 2 (May, 1964), p. 258.

67. Ibid., p. 259.

68. I.N. Fisher, "An Evaluation of Incentive Contracting Experience," *Naval Research Logistics Quarterly*, Vol. 16, No. 3 (March, 1969), p. 65.

69. J.J. McCall, "The Simple Economics of Incentive Contracting," *The American Economic Review*, Vol. 60, No. 5 (December, 1970), p. 839.

70. Scherer, Op. Cit., pp. 257-280.

71. *Rules and Regulations*, Form 4300R Rev. 3-70 (Harrisburg, Pennsylvania: Pennsylvania Department of Highways, March, 1970), p. 8.

72. Personal Communication with Steve Pudlowski, Assistant Professor, Graduate School for Public and International Affairs, University of Pittsburgh, Pittsburgh, Pa., dated May 15, 1974.

73. Grey, Op. Cit., p. 67.

74. Howard Raiffa, Assessments of Probabilities, (Boston, Mass: Harvard University, 1969), unpublished.

75. Savage, Op. Cit., p. 799.

76. Bruno De Finetti, "Methods for Discriminating Levels of Partial Knowledge Concerning a Test Item," The British Journal of Mathematical and Statistical Psychology, Vol. 18, No. 5 (May, 1965), pp. 87-123.

77. Robert L. Winkler, "The Quantification of Judgement: Some Methodological Suggestions," Journal of the American Statistical Association, Vol. 62, No. 320 (December, 1967), pp. 1105-1120.

78. Robert C. Pickhardt and John B. Wallace, "A Study of the Performance of Subjective Probability Assessors," The Journal for the American Institute for Decision Sciences, Vol. 5, No. 3 (July, 1974) pp. 347-363.

79. Hari P. Johri, Donald Quon, and Park M. Reilly, "Decision-Making Under Uncertainty," British Chemical Engineering and Process Technology, Vol. 17, No. 7/8 (July/August, 1972), pp. 597-600.

80. Oliverson, Op. Cit., p. 65.

81. Wittschiebe, Op. Cit., p. 11.

82. Rohrmann, Op. Cit., p. 46.

83. L.E. Frashuer, and D.F. Wanner, "Contract Maintenance in the Industrial Complex," Chemical Engineering Progress, Vol. 67, No. 4 (April, 1971), p. 49.

84. Skolnick, Op. Cit., p. 74.

85. Facilities Project Manual, Op. Cit., pp. 1-1 to 3-10.

86. C.B. McGuire and Roy Radner, ed., Decision and Organization, "Theories of Bounded Rationality, by Herbert A. Simon" (Amsterdam: North-Holland Publishing Co., 1972), Chapter 5.

87. McCall, Op. Cit., p. 844.

88. Alain Enthoven, "What Systems Analysis Is and Is Not," Defense Management Journal, Vol. 4, No. 1

(Winter, 1967-68), pp. 11-14.

89. Clay, Op. Cit., p. 2.

90. Ibid., p. 55.

91. J.A. Sullivan, "A Contractor's View of Contract Maintenance," Chemical Engineering Progress, Vol. 67, No. 4 (April, 1971), p. 47.

92. Scherer, Op. Cit., pp. 260-261.

93. Sargent, Op. Cit., pp. 14-45.

94. Report of the Formal Board of Investigation, Op. Cit., pp. 7-16.

REFERENCES NOT CITED

Atlantic Division, Naval Facilities Engineering Command, Norfolk, Virginia. Personal interviews with selected engineers of the Acquisition Department. November, 1972; March, 1973.

Brinckloe, William D. *Managerial Operations Research*. New York: McGraw-Hill Book Company, 1969.

Brown, Jack "How Much Preventive Maintenance is Enough," *Plant Engineering*, Vol. 28, No. 23 (November 14, 1974), pp. 157-158.

"Contract Maintenance for Air Conditioning Systems," *Power*, Vol. 116, No. 1 (January, 1972), pp. 12-13.

Contracting Manual, NAVFAC P-68. Washington: Department of Defense, December, 1972.

DeGroot, Morris H. "Reaching a Consensus," *Journal of the American Statistical Association*, Vol. 69, No. 345 (March, 1974), pp. 118-121.

Green, Paul E. and Carmone, Frank J. "Evaluation of Multi-Attribute Alternatives: Additive Versus Configured Utility Measures," *The Journal for the American Institute for Decision Sciences*, Vol. 5, No. 2 (April, 1974), pp. 164-181.

Hamburg, Morris *Statistical Analysis for Decision Making*. New York: Harcourt, Brace, and World, Inc., 1970.

Jessup, W. E. *Law and Specifications for Engineers and Scientists*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1963.

Koester, W. F. "Working with Maintenance Consultants," *Plant Engineering*, Vol. 25, No. 20 (September 30, 1971), pp. 41-43.

Papamarcos, John "R & D Priorities and Funding: The Year of Decision," *Power Engineering*, Vol. 77, No. 9 (September, 1973), pp. 52-59.

Savage, Leonard J. *The Foundations of Statistics*. New York: Wiley, 1954.

Trimble, Jerry E., An Analysis of DOD/NASA Contractor Profitability in the Incentive Contract Environment, GSM/SM/71-12 (Wright-Patterson AFB, Ohio: Air Force Institute of Technology, October, 1971).

University of Pittsburgh, Pittsburgh, Pennsylvania. Personal interviews with Dr. Cyrus Mehta of the School of Business. March, 1975.

University of Pittsburgh, Pittsburgh, Pennsylvania. Personal interview with Dr. James Miller of the School of Engineering. October, 1974.

"Upkeep by Outsiders is a Big Time Operation," Power, Vol. 117, No. 4 (April, 1973), pp. 41-42.

Uveges, Joseph A. (ed.) The Dimensions of Public Administration: Introductory Readings. Boston: Holbrook Press, Inc., 1973.

Thesis 158982
F924 Fulgham
A decision theoretic approach to contractual maintenance.
25 APR 75 DISPLAY

Thesis 158982
F924 Fulgham
A decision theoretic approach to contractual maintenance.

thesF924
A decision theoretic approach to contrac
3 2768 001 90691 0
DUDLEY KNOX LIBRARY